STEMPEL

The Distribution of Magnetism in a Steel Wire Subjected to a Varying Field Along its Length

Graduate School

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THE DISTRIBUTION OF MAGNETISM IN A STEEL WIRE SUBJECTED TO A VARYING FIELD ALONG ITS LENGTH

BY

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

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ENTITLED The distribution of magnetism in a steel wire subjected to a varying magnetic field along its length

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF Master of Arts

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HEAD OF DEPARTMENT OF Physics

1906
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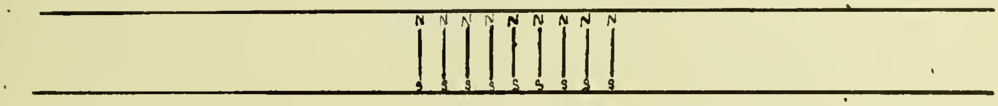
THE DISTRIBUTION OF MAGNETISM IN A

STEEL WIRE SUBJECTED TO A VARYING FIELD ALONG ITS LENGTH.

In L'Eclariage Electrique 23 pp 397-408 is a discription of Poulsen's telegraphon. This apparatus consists of an electro-magnet put in circuit with a telephon transmitter, and between the poles of which a steel ribbon is caused to pass at a velocity of about thirty-six meters per minute. The current, varied by speaking into the transmitter, induces upon the steel wire magnetism which varies in strength similarly to the current which produced it. If this wire is then taken and again passed through a similar piece of apparatus with a telephon receiver in circuit, the original sounds are reproduced. All who have heard one of these instruments working and with whon I have spoken say that the reproduction is very weak but extremely pure. It was this that suggested that it might be of scientific interest to study the distribution of magnetism along a wire which has been passed at a high velocity through an alternating magnetic field.

One of the first things noted is that the wire is not transversely magnetized, as is stated in every article discribing the telegraphon (Journal of the Institute of Electrical Engineers of 1901 p 38 and Electrical World and Engineer 39, p 911 May 24,1902). In the case of all the samples tested, I found no such state of magnetization. In all probabilities the magnetization is transverse at the moment it is impressed upon the wire, but, owing to the extreme proximity of the poles formed, the magnetism would be largely destroyed if left in that position, and so it is highly probable that the elementary magnets formed along the wire are turned about through an angle of 90 degrees, for in such a posi-

tion there would be no free (that which is left after equal quantities of opposite signs have been neutralized) magnetizations of opposite signs which would be very close together and the magnetic state of the wire would be stable and permanent. Such a turning of the elementary magnets could not. however, result from the magnets alone, for one has no tendency to turn the other, since the like poles on one side of the wire repell each other with the



same force as do the like poles on the other side. But if one of the pole pieces of the exciting magnet is nearer the ribbon than the other, it would tend to drag the elementary magnets with it and this start the rotation which the elementary magnets would then complete on their own account, for when they are turned through an angle of about 50 degrees there would be a north pole close to a south pole of the magnet preceeding or vice versa and they would tend to pull each other around into line (See Fig.2). There seems to be evidence that this is the state of affairs in the steel wire for I have not been able to detect magnetizations of opposite polarity at a single point in the wire and I tested the wire on all sides. I have found that the magnetization is very marked if the wire is passed very close to one of the pole pieces and at some distance from the other, and that when the pole pieces are equally distant, practically no magnetization is left upon the wire. Let us see what would happen in a few special cases of such a turning of the elementary magnets. In Fig. 1 we

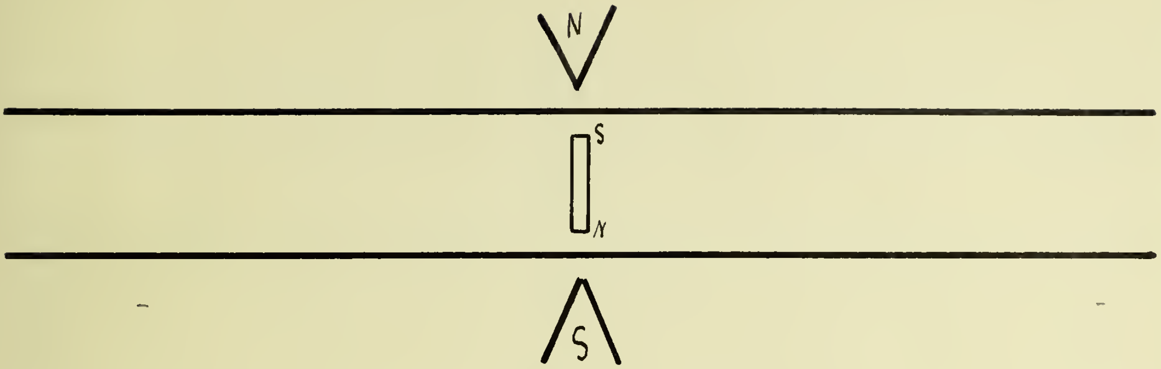


Fig. I.

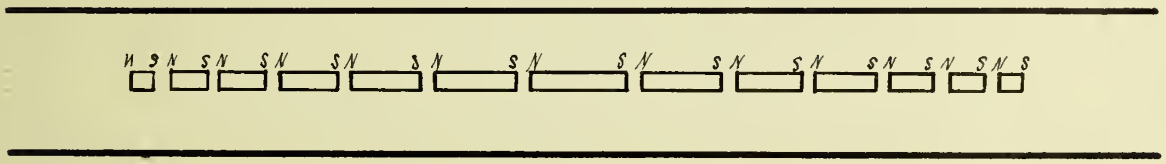


Fig. II.

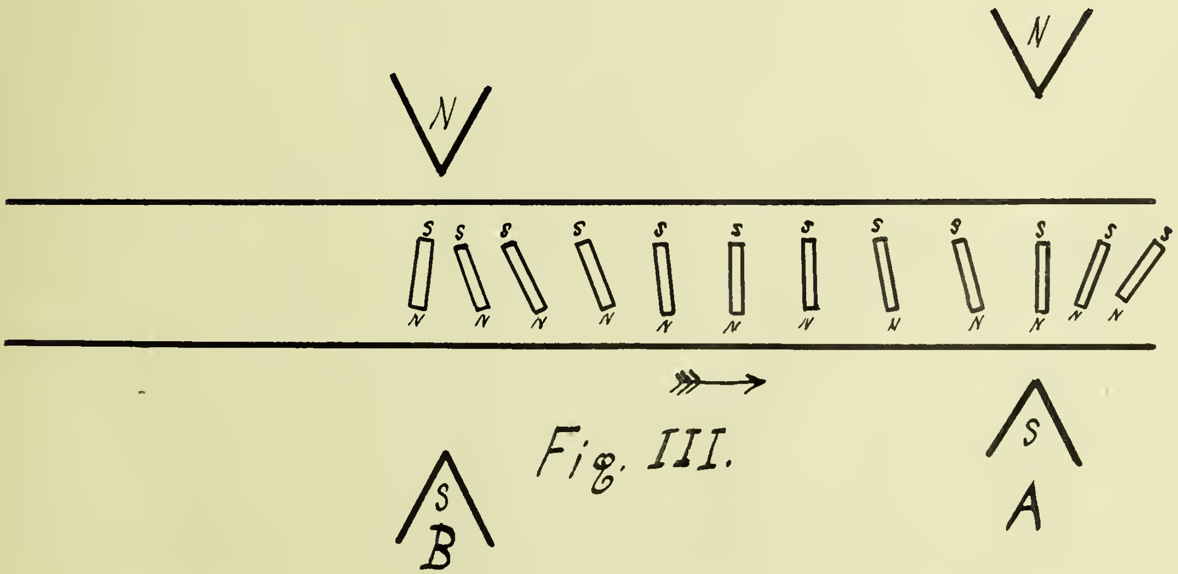


Fig. III.

have the state of affairs just at the time that the magnetization is being impressed. The magnetization is transverse. But as the wire comes out from under the influence of the pole pieces, the magnets turn and align themselves along the wire. The pole of one magnet which comes, by this rotation, into proximity to the opposite pole of another, is in general of a different strength than the one preceeding and consequently it s corresponding opposite pole, and so there is a resulting free magnetism after equal poles of opposite polarity have annulled each other. In Fig.2 the length of the small rectangles which represent the elementary magnets indicate the strength of the magnets. It is this predominating magnetism which we measure and which produces the effects which make the telegraphon possible. We would thus expect the maxima and minima on the wire to be shifted with respect to the points of greatest and least magnetizing force, for the greatest residual effect would be at the points of most rapid change. Thus we should expect a lag or a lead in the magnetization curve with respect to the magnet~~i~~izing curve, and such is very probably the case as we shall see later. Again, if the pole pieces for impressing the state of magnetization are exactly perpendicular to the length of the steel wire, two elementary magnets of equal strength would have no tendency to turn due to themselves or the pole pieces, provided the pole pieces were an equal distance from the wire. But let us suppose the following conditions. At A (Fig.3) let the bottom pole piece be nearer to the wire than the top one. It will tend to turn the elementary magnets clockwise, but at the

point B where the upper pole piece is nearer to the wire than the bottom one, the magnets would tend to turn counter-clockwise. Such a state of affairs can be imagined and we would have as a consequence two adjacent maxima of the same sign with no sign of any magnetization between the two points, for the points of the most rapid increase in the magnetizing force would have the same pole predominating. This has been realized in a single instance and it was an unexplainable point for some time how an alternating

N S N S N N S N S N

current could produce upon a wire two magnetic poles of the same sign at the same distance apart as the distance between alternating poles preceeding and following this region.

The above gives one source of a lag or lead of the magnetization curve with respect to the magnetizing curve. There is, however, another point which came up. Does it take any time for a piece of steel to reach its point of maximum magnetization after the magnetizing force is turned upon the steel? To solve this question it was first thought well to pass a sample of steel at a high velocity between the poles of an excited magnet a number of times, measuring the state of magnetization on the steel each time. We would thus get the added effects due to successive equal exposures to the field and from the curve we could get the time element.

First of all it was necessary to find some method of measuring the magnetization. Magnetometer methods in the ordinary form were not applicable because the mathematics of such methods is accurate

only when the sample is either very long or it is in the form of an ellipsoid of revolution. The sample used had to be very short and so these methods gave but little encouragement. I devised, however, the following method. A spool, wound full of very fine magnet wire, was slipped on the bottom end of a vertical paper tube suspended so that a carriage could fall freely down the tube (See Fig.4). This carriage was of such a length that its lower end broke the circuit, composed of the coil just mentioned and a ballistic galvanometer, just at the instant when the sample, being properly fastened to the carriage, was half way through the above coil. We would thus get a throw proportional to the lines of force radiating from the sample. The readings got with this piece of apparatus were exceptionally constant, the variation being about five tenths of one percent from the mean.

The apparatus used for making the exposure was simply a wooden disk (See Fig.5), which could be rotated at a very high velocity. Near the circumference were a number of holes into which the sample could be placed and which was so placed that it passed exactly between the poles of the excited magnet. It is to be noted that the sample was not allowed to pass the magnet but once as the residual magnetism had an effect upon the sample. It was therefore necessary to propell the disk with a very heavy weight working on a long leaverage in order to give the disk a high velocity in going once around. The data collected in this way looked promising at first, but it was soon realized that at least some and probably all of the effect was due to another cause.

Fig. IV.

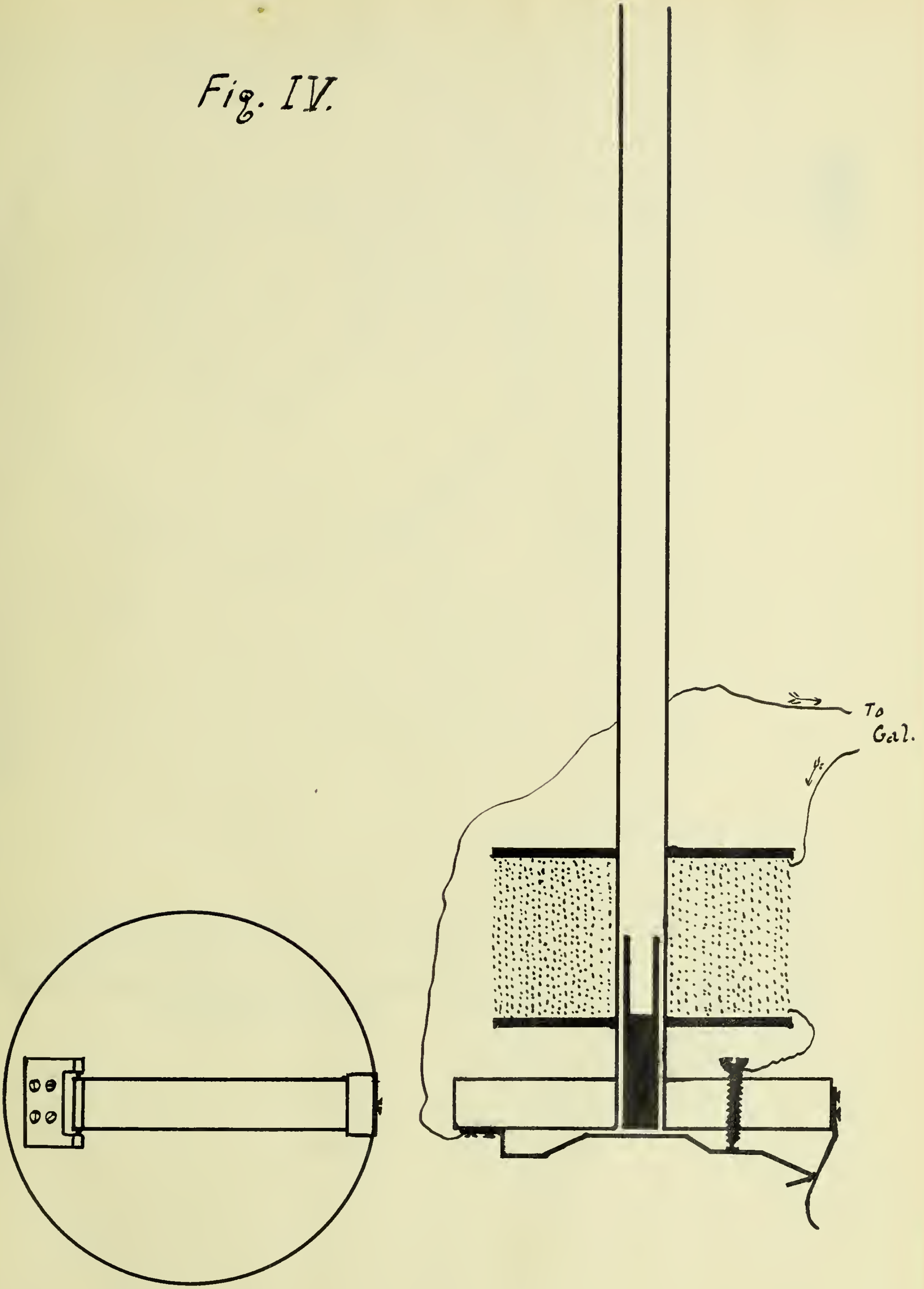
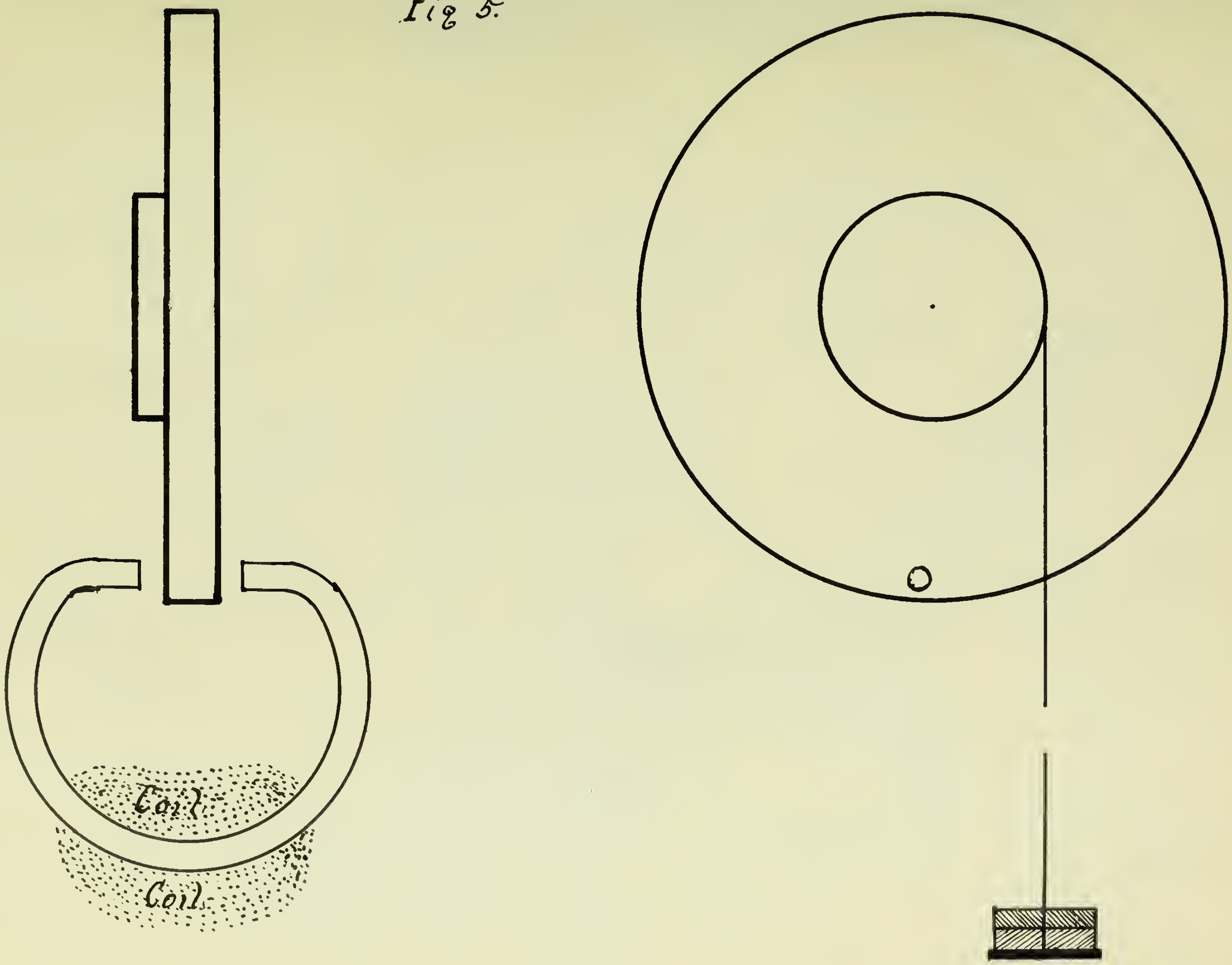


Fig 5.



I

Time.	Reading.	Deflection.	Zero.
0	88.35	.55	88.9
1	80.7	8.2	88.9
2	80.05	8.4	88.9
3	79.95	8.95	88.9
4	79.7	9.2	88.9

II

Time.	Reading.	Deflection.	Zero.
0	87.6	1.25	88.85
1	86.	2.85	88.85
2	85.8	3.05	88.85
3	85.7	3.15	88.85
5	85.55	3.3	88.85
10	85.5	3.35	88.85
Large	85.55	3.3	88.85

The first set of the above data was taken with the sample just short enough to clear the pole pieces of the electro-magnet. The same weight was used in propelling the disk throughout this work and since the disk was started from the same point each time, the time of exposure was constant and was taken as our arbitrary unit of time in the above table. The second set of data is the same as the first except that the sample was filed shorter and thus left a greater clearance space. It will be noted that the maximum effect was reached much sooner in this case than in the first and showed that the effect we were measuring was due to the fact that the introduction of a piece of iron into a magnetic circuit would decrease the reluctance and we would have an inductive effect, that is the field would tend to increase while the steel went through. On cutting off the sample a decrease of the effect was noted and when about a third of the sample was cut away (the sample was about three centimeters long) no more lag could be noticed. The sample was hard tool steel.

To investigate this question of time element without complications due to inductive effects, it was decided to return to the telegraphon arrangement and to vary the strength of the field instead of changing the position of the sample in the field which would change the reluctance of the magnetic circuit. An optical occillagraph, made at the University of Illinois, now came most beautifully to our aid. It was used as follows. The occillagraph had in one end a horizontal opening outside of which could be mounted a long vertical closed box and on the inside of which was a carriage for holding a photographic plate. The plate could thus be made to fall past the opening and the beam of light, vibrating horizontally and coming from the occillating mirror of the occillagraph, regestered upon the plate a picture of the curve corresponding to the alternating current which was passing through the occillagraph. One modification was made in the above arrangement. The photographic box (See Fig.6) was made double and a strip of wood fastened lengthwise on the back of the carriage (See Fig.7) which projected through the partition between the two compartments, the partition being cut away in the center to allow the free movement of the carriage. Upon the strip on the back of the carriage were mounted the various steel ribbons and wires to be investigated. In the second chamber was mounted an electro-magnet (See Fig.8) thoroughly laminated, in the form of a rectangle. The pole pieces were ground down to a very narrow edge and the rectangle so placed that the ribbon on the carriage passed between the pole pieces, the narrow edge being at right angles to the length of the ribbon. The purpose of the narrow edge was to con-

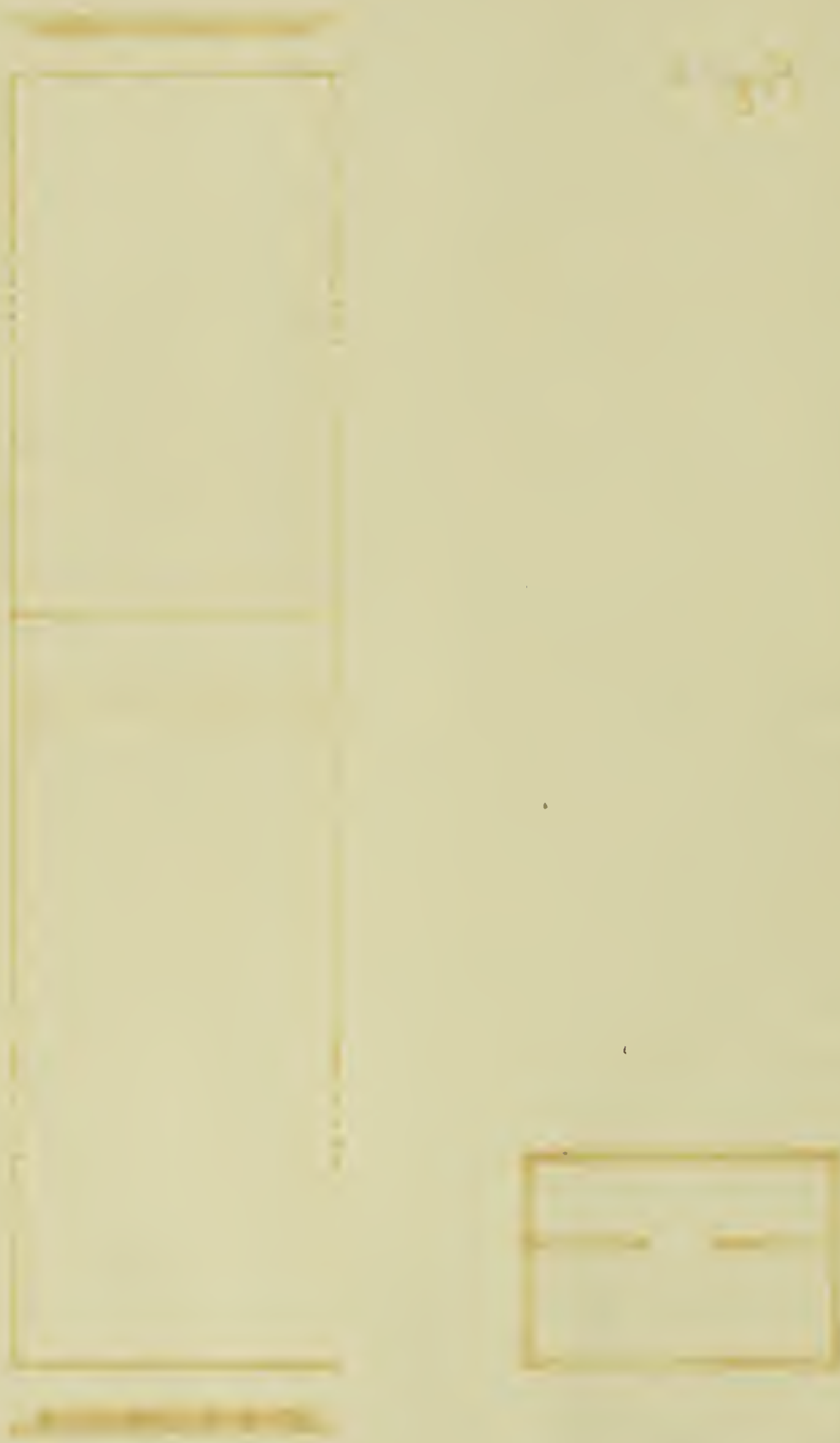


Fig. 6

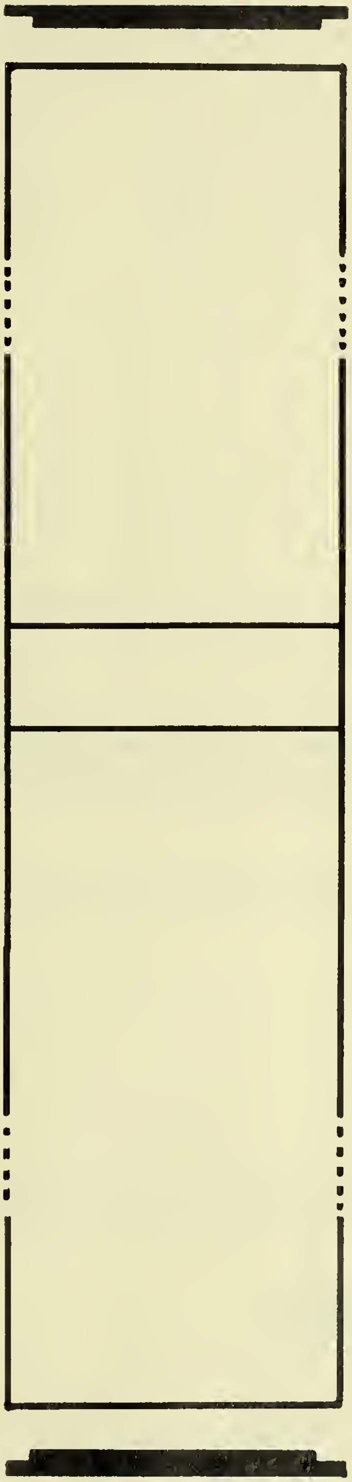
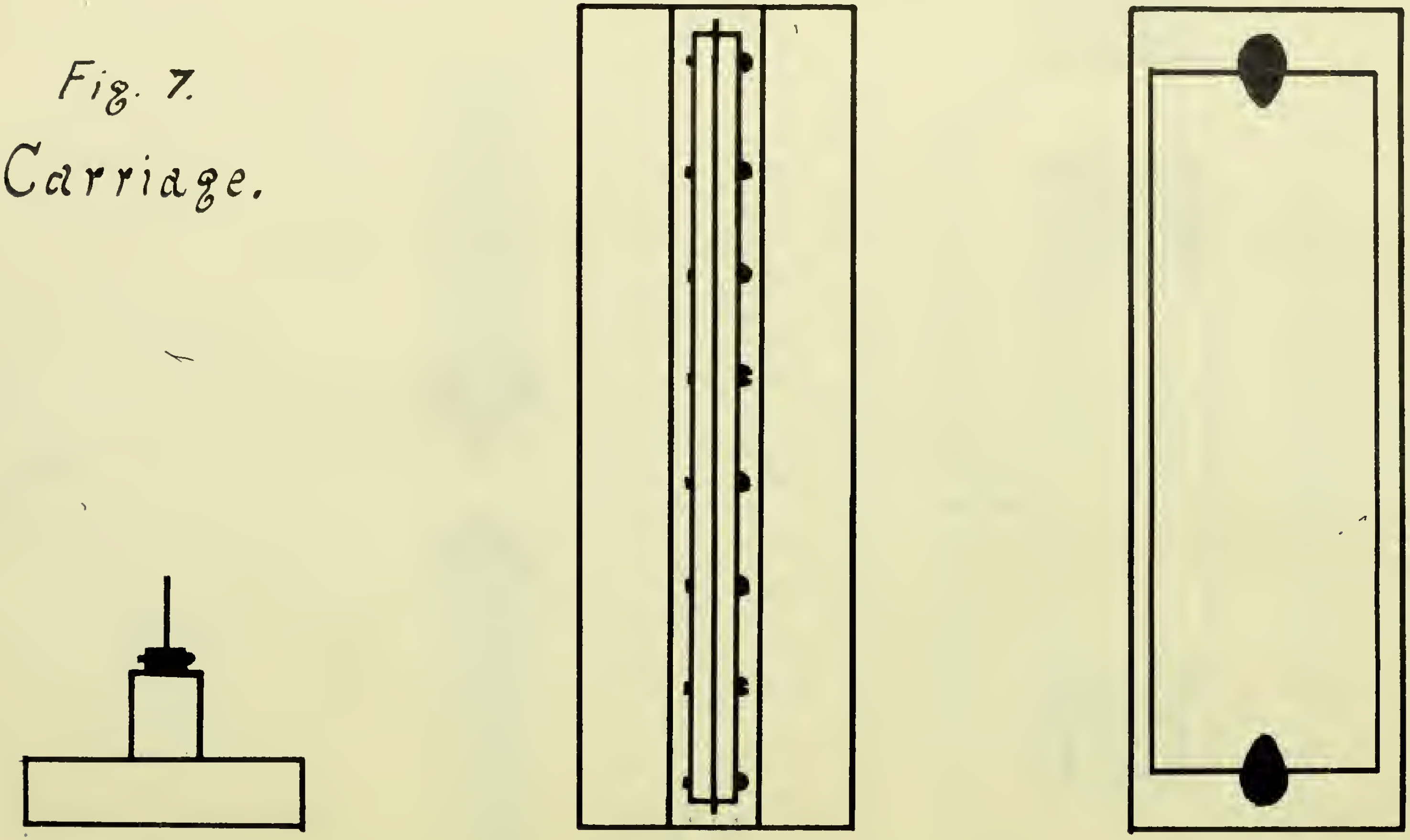
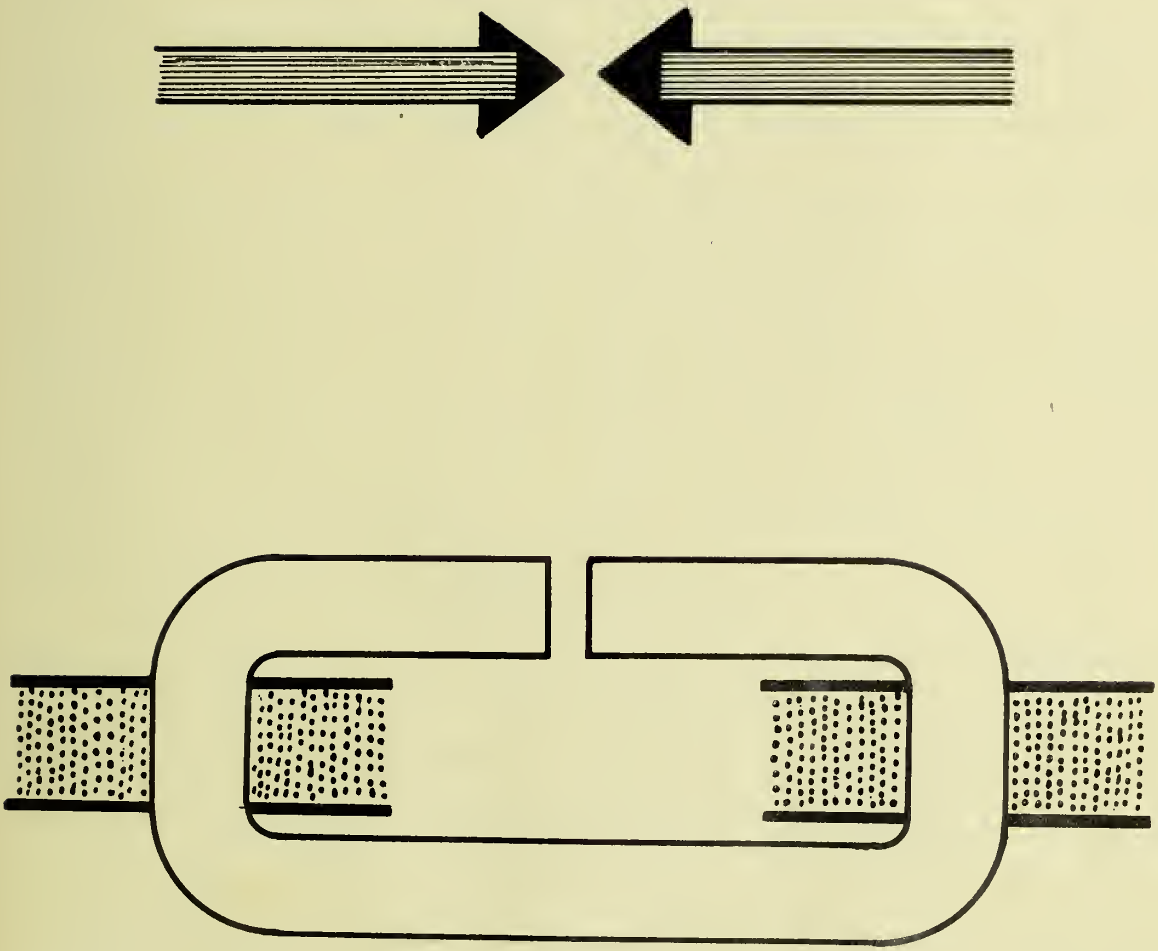


Fig. 7.
Carriage.



Cross Section. Back. Front.

Fig 8.



centrate the magnetic field. Then by allowing the alternating current to pass in series through the electro-magnet in the photographic box and through the occillagraph, and by allowing this carriage with a photographic plate on one side and a steel ribbon on the other, to fall past the opening in the occillagraph box and the electro-magnet respectively, we were able to get a magnetic curve and an optic curve representing our alternating current side by side so that we could compare them.

It only remained for us now to find a method of detecting and measuring the distribution of magnetism along the ribbon or wire as the case may be, for getting the required data. This looked like an easy task but the practical difficulties were many.

The occillation method was first tried. A magnetometer needle was suspended on a silk fiber about fifteen centimeters long in a glass tube to avoid air currents and the vibrations counted at equal intervals along the ribbon. This method gave no reliable data and was soon abandoned.

The following method was then tried. Two pieces of soft Swedish iron were bent into the form of a wide letter U (Fig.9) and mounted on an upright so that the ends on the one piece faced those on the other. The bottom ends were ground to an edge in the plane of the rectangle formed by the two pieces of iron. The upper ends were ground to a rather small cone point. Between the lower edges the ribbon or the wire could be drawn along, and between the upper cone points a magnetometer needle was suspended. From the fact that the wire or ribbon was magnetized along the wire

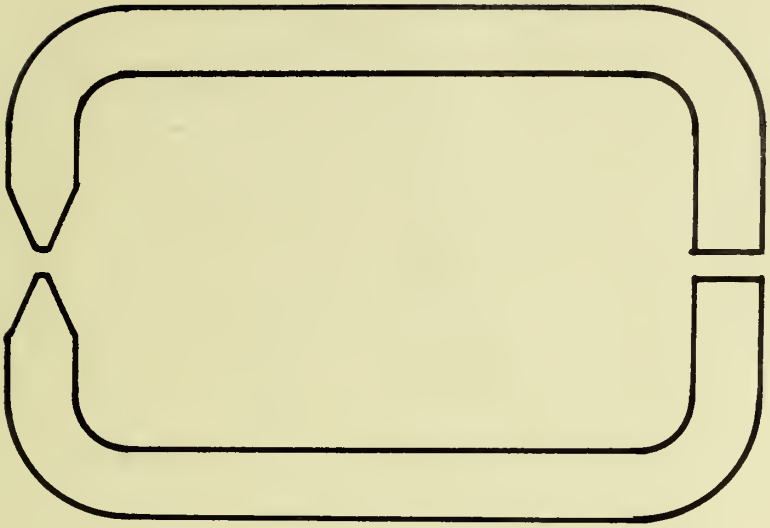
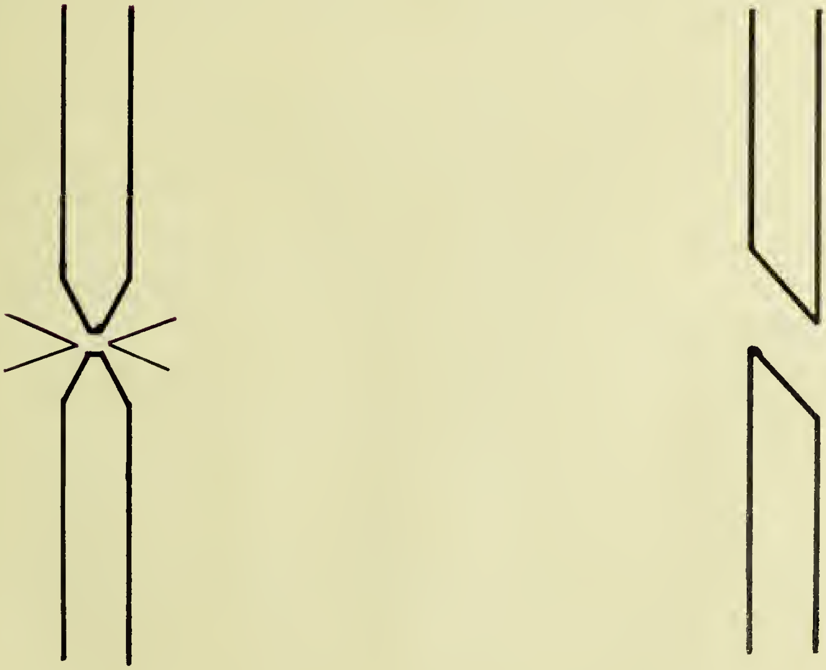


Fig. 9.



and not transversely, the edges at the bottom were displaced one half inch. We thus measured the difference between two successive points along the wire or ribbon and not the absolute value. This would produce a shift of our curve, for the points of the most deflection would be the points of most rapid change in the magnetization and the points of least deflection those of no change or the points of maximum or minimum magnetization, provided we begin to count at the point midway between the positions of the lower edges of our iron rectangle for the first reading, or in other words, if the readings are to correspond to points midway between the edges on our rectangle. From what has been said in regard to transverse magnetization, we see that the shift due to this method of relative measurement is just annulled because of the fact that the points of greatest magnetization are the points of the most rapid change in the magnetizing field and not the points of strongest field.

There is still another shift which must be corrected for and that is the shift due to the fact that the point where the beam of light strikes the photographic plate may not be in the same horizontal plane with the pole pieces of the magnetizing electro-magnet, which assumption is made in comparing the curves. This was carefully adjusted to zero before each observation.

Another point which gave some truble at first was that our magnetometer needle when placed between the conical points of our iron rectangle was attracted towards the iron and took up a position parallel to the air gap. The position perpendicular to the air

gap was a position of unstable equilibrium, and it was this position which we must have stable. To do this we placed on each side of the air gap one arm of a U shaped piece of hard tool steel, not magnetized. A hard tool steel was used in order that its influence upon the magnetometer, due to the very slight magnetization, should be as nearly as possible constant. The inside of the two arms of the U shaped steel was ground to an edge with an angle of about 30 degrees. The magnetometer needle had about a 10 c.m. suspension in a glass tube and the space about the needle was closed in to prevent the effects of air currents. The outside magnetic effects were then screened from the apparatus by surrounding it with a six inch gas pipe with a window in the side through which the suspended mirror could be viewed and the readings taken. Since the carriage upon which the steel ribbon was fastened was about 10 inches long and since it had to travel so that the steel ribbon could be examined from end to end, the above gas pipe could not cover all the parts of the magnetometer system and the lower ends of th the soft iron rectangle projected below the pipe. These collected a good many stray magnetic lines and so a large cylinder of tin was placed around the whole lower portion, large enough to allow a free movement of the carriage back and forth. A large piece of tin under the whole apparatus completed the screening of the magnetometer system from outside influences. The apparatus in this shape worked very satisfactorily as will be seen from the following data where the readings taken at different times for the same point don't vary greatly.

The alternating current used was supplied from an alternator driven slow enough to give a frequency of about twenty cycles per second. The field was excited by a current from a storage battery giving about twenty-four volts. The field of the occillagraph was excited by a small current from a storage battery. This current was adjusted so that the beam of light vibrated back and forth over about two inches of the photographic plate. This adjustment was made, of course, with the electro-magnet in the camera box in circuit. All adjustments having been made, the steel to be examined was clamped on the carriage, the whole camera box taken to the dark room, a four by five photographic plate, cut in two lengthwise (we had no more convenient size at hand) placed into the carriage, the carriage replaced in the top of the camera box, and the whole taken back to the occillagraph. The alternator was then set in motion, the two field currents turned on, the light of an arc thrown upon the mirror of the occillagraph from the proper direction, and the carriage released by withdrawing a rod which projected into the camera box and held the carriage up. The camera was then taken back to the dark room and the plate developed. The steel was then examined without removing it from the carriage, which was spaced off in one-fourth inch intervals so that at each point we could determine the magnetic effect on one side and the distance from an arbitrary line, drawn parallel to the length of the plate, to the curve on the other side of the carriage. The two curves thus obtained are shown in the following pages. The numbers running from one to sixteen are one-eighth inch intervals measured from the above

arbitrary line to the curve from which data the photographic curve was plotted after correcting the data to bring the curve to the same scale as the magnetic which was done as follows. In the magnetic data we obtained two extreme readings which being proportional to current, can represent current in some arbitrary unit. If then we equate the difference between these extreme readings to the difference between the extreme readings got from the photographic curve multiplied by (x), we get a coefficient (x) which when multiplied into the photographic readings converts them into the same arbitrary unit which expresses the magnetic readings. This makes the curve of the same scale as they are already to the same scale lengthwise, and we can compare the current values at points along the wire and plate. We must, however, add a constant to the readings got by multiplication since the two curves have not the same origin. We will make the lower minima in each case coincide and the constant which must be added we will designate by (y) in the data.

Let us now examine the curves and see what we can say about them. It will be seen that the alternating current used was one of double periodicity, that is to say a curve of low frequency superposed upon one of higher frequency. It will also be seen that the current values for one curve are higher than those at the corresponding points on the other curve. This condition changes from one curve to the other. These points are marked by a red cross at the top of the paper and the arrows indicate the region in which the photographic curve has the larger value. This increase of slope in the photographic curve is true only in general. If one

examine the separate parts he will find that sometimes the magnetic curve and then the photographic curve has the greater slope. The fact that the increase favors in general one curve on the down slope and the other on the up slope goes to show that the effect is due to a displacement of one curve with respect to the other. That this is partly true may be seen in that if we add the excesses of one curve over the other throughout a complete period, we find that the excesses of the first over the second practically neutralize the excesses of the second over the first. A finer adjustment of the beam of light on the photographic plate and the electro-magnet in the photographic box is necessary to determine whether this displacement of one curve is due to a lag in the magnetization or inaccuracy in adjustment. It seems therefore that the magnetic curve is as good a representation of our alternating current as the optic curve. We might therefore use this method in determining the characteristics of an alternating current instead of using the occillagraph which would, in many cases, be more convenient. More work along this line will undoubtedly lead to some very important and interesting conclusions.

STEEL CLOCK SPRING

Thickness 12 m.m.

Width .25 m.m.

Magnetic Data.

								Average
1	13.7	13.6	13.9	14.1	12.5	13.9	13.9	13.7
2	26.5	28.4	30.7	31.2	27.4	30.6	30.1	29.3
3	30.2	28.2	30.1	30.4	29.5	31.	30.5	30.
4	26.4	26.7	27.1	27.4	26.2	27.5	24.4	26.5
5	27.3*	29.7	29.9	30.2	28.9	30.2	30.	29.8
6	29.1	30.9	32.3	32.7	31.5	31.5	31.3	31.3
7	29.2	29.	29.3	29.7	28.4*	29.8	29.8	29.4
8	25.1	24.9	25.1	25.7	24.2*	25.5	25.3	25.3
9	24.7	24.4	24.6	24.8	23.6*	24.9	25.	24.7
10	28.4	27.7	28.2	28.3	26.9	28.5	28.	28.
11	24.2	23.6*	24.2	24.2	22.9*	24.2	24.3	24.2
12	17.2	16.7	17.2	17.7	15.9*	17.1	17.4	17.2
13	15.2	15.5	16.3	16.1	13.9	15.3	15.7	15.4
14	25.4	25.5	27.	28.*	25.9	25.2	24.	25.5
15	28.7*	35.	33.8	34.6	35.2	34.4	34.2	34.2
16	34.8	39.8	39.3	39.8	38.5	35.4	40.	38.2

Photographic Data. / Vibration Data.

(Numbers are proportional to field)

	Original.	Transformed	Vibration
1	.5	16.5	.4
2	4.5	25	.5
3	9.	34.6	.34
4	7.25	30.8	.45
5	8.5	33.5	.47
6	11.	38.8	.63
7	11.5	39.9	.59
8	6.	28.2	.48
9	2.5	20.7	.41
10	4.5	25.	.59
11	3.75	23.4	.45
12	1.25	18.1	.34
13	0.9	15.4	.27
14	2.75	21.3	.32
15	7.75	31.9	.3
16	9.5	35.6	.29

x=2.13
Y=15.4

* These numbers are not reliable and have been omitted in the average.

STEEL CLOCK SPRING.

Thickness 12 m.m.

Width .25 m.m.

Magnetic Data.

								Average Def,
1	29.5	28.9	28.9	29.7	28.6	29.1	29.	29.1
2	25.3	23.5	28.8*	24.1	23.5	24.	25.5	23.9
3	5.	4.3	6.	8.1	9.8	6.	8.8	6.9
4	17.8	12.45*	_.2*	15.6*	19.7	19.1	18.	18.6
5	34.7	34.8	11.4*	28.5*	34.8	35.4	34.4	34.8
6	26.5	26.85	26.1	28.3*	29.5*	30.7*	26.2	26.4
7	26.9	16.1*	25.7	27. 05	25.6	27.2	20.5	25.5
8	52.*	42.2	45.1	45.8	45.4	47.2	45.6	45.2
9	61.5*	69.	61.*	69.	68.5	----	----	68.8
10	33.2	33.3	31.45	31.4	28.8	30.7	32.8	32.4
11	4.6*	21.4*	15*	8.5	7.	6.	7.4	7.2
12	13.4	21.2*	15.5	15.4	15.1	12.1	12.8	13.7
13	25.	27.8	27.	27.4	23.5	24.5	24.	25.3
14	8.6	9.8	5.5	10.5	5.8	8.7	5.6	7.8
15	33.6	33.7	34.6	28.4	31.	31.8	32.8	32.5
16	49.2	48.85	47.	49.9	46.5	46.2	47.9	47.8

Photographic Data. / Vibration Data.

(Numbers are proportional to field)

	Original.	Transformed.	Vibration Data
1	5.	30.3	.36
2	3.75	26.2	.25
3	1.	12.7	.17
4	1.	12.7	.16
5	6.75	40.8	.13
6	10.	56.8	.14
7	7.5	44.6	.11
8	10.25	58.	.11
9	12.5	69.1	.10
10	10.25	58.	.08
11	5.5	34.8	.08
12	3.25	23.7	.18
13	5.5	34.8	.18
14	2.75	21.3	.23
15	0.0	7.8	.44
16	6.25	40.8	.36

X = 4.9
Y = 7.8

* These numbers are not reliable and have been omitted in the average.

PIANO WIRE.

Diameter .82 m, m.

	Magnetic Data.				Photographic Data.	
				Average.	Original.	Transformed
1	24.	23.7	24.1	23.9	9.5	27.7
2	25.3	25.1	25.1	25.2	11.5	31.3
3	27.6	27.5	27.8	27.6	13.	33.9
4	30.6	30.7	31.1	30.8	14.25	36.1
5	33.	32.65	33.75	33.1	14.25	36.1
6	32.1	31.55	32.6	32.1	12.	32.2
7	29.3	28.8	29.3	29.1	7.25	23.7
8	25.4	25.	25.7	25.3	4.5	18.9
9	23.9	23.7	24.3	23.9	3.	16.2
10	26.8	26.4	27.7	26.9	4.25	18.4
11	28.6	28.2	30.1	28.9	5.75	24.7
12	29.	27.7	29.25	28.6	5.	19.8
13	23.2	23.15	24.5	23.6	3.25	16.7
14	16.4	17.35	19.15	17.6	1.5	13.6
15	12.4	13.1	11.6	12.3	.5	11.8
16	11.75	11.3	9.5	10.9	0.0	10.9
17	15.55	14.7	12.	14.1	.5	11.8
18	21.5	21.4	16.35	19.7	3.5	17.1
19	23.1	26.5	21.75	23.8	7.	23.3
20	26.6	29.2	24.7	26.8	9.5	27.7
21	27.8	28.25	26.7	27.6	11.5	31.3
22	25.85	26.4	24.3	25.5	11.25	30.8
23	23.	22.9	21.45	22.5	9.5	27.7
24	21.7	21.8	19.3	20.9	9.25	27.3
25	24.6	23.9	21.7	23.4	10.75	29.9
26	28.45	28.2	24.9	27.1	12.25	32.6
27	33.3	32.8	31.8	32.6	13.5	34.9
28	37.5	38.7	36.4	37.5	15.	37.5
					X=1.77	
					Y=10.9	

This wire was straightened by heating and not by hammering.

IV

PIANO WIRE.

Diameter .82 m.m.

	Magnetic Data.				Photographic Data.	
				Average.	Original.	Transformed.
1	26.	25.9	25.8	25.9	11.5	32.[illegible]
2	24.1	24.2	23.95	24.1	9.75	29.4
3	22.1	22.15	22.15	22.1	8.25	26.7
4	23.65	23.5	23.55	23.5	9.5	29.
5	28.4	27.6	27.65	27.9	11.5	32.6
6	32.05	31.45	31.3	31.6	13.	35.4
7	35.95	35.25	35.5	35.6	13.5	36.3
8	36.8	36.15	36.1	36.4	13.5	36.3
9	32.9	32.3	31.8	32.3	11.5	32.6
10	26.45	27.9	26.25	26.8	8.25	26.7
11	21.45	22.35	22.85	22.2	5.5	21.7
12	20.5	21.2	21.65	21.1	3.25	17.5
13	21.65	21.55	21.9	21.7	4.25	19.4
14	24.65	24.2	24.4	24.4	5.75	22.1
15	27.4	26.75	26.6	26.9	5.25	21.2
16	25.55	25.3	25.15	25.3	3.75	18.5
17	20.	20.1	20.3	20.1	2.25	15.7
18	15.75	16.35	16.8	16.3	1.	13.4
19	11.45	12.25	12.8	12.1	.25	12.1
20	11.8	12.35	13.4	12.5	.25	12.1
21	17.3	17.7	18.	17.7	2.25	15.7
22	23.6	23.2	23.05	23.3	6.	22.6
23	28.2	27.15	26.7	27.4	9.	28.1
24	29.5	28.5	27.9	28.6	10.75	31.3
25	28.85	28.3	27.85	28.3	10.75	31.3
26	26.3	26.1	26.	26.1	9.	28.1
27	22.95	22.7	23.3	22.9	8.5	27.2
28	23.6	23.1	23.65	23.5	9.75	29.4
29	26.85	26.2	26.55	26.5	11.25	34.5

$X = 1.83$
$Y = 11.6$

This wire was straightened by heating slightly and not by hammering.

PIANO WIRE.

Diameter .82 m.m.

	Magnetic Data.				Photographic Data.	
				Average.	Original.	Transformed.
1	23.9	23.9	24.3	24.	11.	31.3
2	22.75	22.9	23.	22.9	12.75	34.2
3	23.	23.2	23.35	23.2	9.75	29.2
4	24.55	24.5	24.25	24.3	11.25	31.7
5	27.75	27.75	27.3	27.6	13.	34.6
6	31.5	31.1	30.55	31.	14.25	36.7
7	36.3	35.3	34.5	35.3	15.	37.9
8	38.6	38.	37.15	37.9	14.75	37.5
9	36.5	35.8	35.35	35.9	12.25	33.3
10	31.4	31.4	31.	31.3	8.75	27.5
11	25.5	26.4	26.4	26.1	6.	23.
12	24.2	25.	24.85	24.7	4.25	20.1
13	23.	23.9*	23.85	23.6	4.5	20.5
14	27.1	24.7*	24.5	25.4	6.75	24.2
15	26.7	26.5*	26.05	26.4	6.75	24.2
16	25.9	26. *	25.6	25.8	4.25	20.1
17	22.7	22.9*	22.7	22.8	3.	18.
18	19.2	20.05*	20.2	19.8	1.75	15.9
19	14.6	15.9*	16.25	15.8	.5	13.8
20	12.1	13.1*	13.85	13.	0.0	13.
21	13.2	13.1*	13.5	13.2	1.5	15.5
22	14.8	14.8#	14.7	14.7	4.5	20.5
23	19.6	19.6#	19.45	19.6	7.5	25.5
24	22.5	22.7#	22.3	22.5	9.5	28.8
25	24.5	24.5#	24.5	24.5	11.	31.3
26	25.6	25.8#	25.7	25.7	10.25	31.7
27	24.25	24.5#	24.7	24.5	9.	27.9
28	22.	22. #	22.1	22.	8.25	26.7
29	20.7	21. #	21.2	20.9	9.75	29.2
30	21.2	21.6	21.65	21.5	11.	31.3
31	23.75	24.2	24.1	24.	12.5	33.8

X==1.66
Y=13.

* These readings were taken during a heavy thunder storm when the magnetometer needle was very restless.

\# These readings were taken during the quiet rain following the above storm.

This wire was hammered and twisted in straightening.

PIANO WIRE.

Diameter .82 m. m.

	Magnetic Data.				Photographic Data.	
				Average.	Original.	Transformed.
1	24.5	24.35	24.6	24.5	2.25	17.5
2	25.1	25.05	25.2	25.1	5.25	23.
3	27.3	26.95	27.15	27.1	5.	22.5
4	26.5	26.35	26.2	26.4	3.25	19.5
5	23.2	22.65	22.7	22.9	1.75	16.6
6	18.25	17.95	18.	18.1	.75	14.8
7	14.2	14.	14.15	14.1	0.0	13.4
8	13.	13.2	14.	13.4	1.	15.2
9	14.75	14.9	15.3	15.	4.25	20.3
10	17.3	17.35	17.3	17.3	7.75	27.5
11	20.5	19.9	19.9	20.1	9.75	31.1
12	22.2	21.8	21.75	21.9	10.25	32.1
13	21.75	21.65	21.6	21.65	8.75	29.3
14	20.5	20.45	20.6	20.5	7.75	27.5
15	21.	21.	21.4	21.1	9.	29.8
16	23.8	24.	23.75	23.9	10.75	33.
17	29.5	29.05	28.55	29.	12.25	35.7
18	33.75	33.6	33.5	33.6	13.25	37.5
19	37.8	37.8	37.8	37.8	13.75	38.4
20	38.4	38.6	38.75	38.5	13.	37.
21	36.8	36.8	37.2	36.9	9.75	31.1
22	33.85	33.8	34.65	34.1	6.75	25.7
23	30.9	30.7	31.4	31.	4.75	22.
24	28.25	28.5	28.9	28.55	3.75	20.2
25	27.	27.1	27.7	27.2	4.75	22.
26	28.25	28.4	28.7	28.5	5.5	23.4
27	30.	29.9	30.	30.	5.25	23.
28	29.45	29.65	29.5	29.5	4.25	20.3
29	26.9	26.9	26.65	26.8	2.75	18.4
30	23.2	23.45	23.4	23.4	1.25	15.7
31	18.2	18.35	17.9	18.1	.5	14.3

X = 1.22
Y = 13.4

This wire was straightened by hammering.

VII

PIANO WIRE.

Diameter .82 m.m.

	Magnetic Data.				Photographic Data.	
				Average.	Original.	Transformed.
1	27.2	27.15	26.75	27.	11.	31.6
2	31.4	30.9	30.45	30.9	12.75	34.6
3	35.35	34.65	35.05	35.	13.75	36.3
4	36.45	36.4	36.1	36.3	13.5	35.9
5	33.65	33.45	33.7	33.6	10.5	30.8
6	29.55	29.2	29.5	29.4	7.25	25.2
7	25.95	25.4	25.65	25.6	4.25	20.1
8	24.15	23.8	24.8	24.3	3.	18.
9	24.95	24.4	24.6	24.7	4.25	20.1
10	27.4	26.8	27.05	27.1	5.5	22.5
11	28.3	29.1	28.	28.5	4.5	20.6
12	26.	26.	26.	26.	2.5	17.2
13	22.15	21.25	21.3	21.6	1.25	15.
14	17.4	16.9	17.2	17.1	.25	13.5
15	13.3	13.15	13.45	13.3	.25	13.5
16	13.75	13.95	14.45	14.1	1.75	15.9
17	20.25	19.95	19.35	19.9	5.	21.4
18	23.75	24.5	24.5	24.4	8.5	27.4
19	27.25	27.2	27.6	27.4	10.5	30.8
20	26.55	27.1	27.45	27.	11.	31.6
21	25.35	25.05	25.35	25.3	9.5	29.1
22	22.95	22.65	22.85	22.8	8.	26.5
23	21.5	21.25	21.45	21.4	9.	28.2
24	22.45	22.1	22.25	22.3	10.25	30.3
25	26.35	25.6	26.	26.	11.5	32.5
26	31.	30.4	30.25	30.6	13.	35.
27	35.95	35.7	35.55	35.7	13.75	35.9
28	36.85	36.75	36.5	36.7	14.	36.7
29	33.	33.15	32.8	33.	12.	33.5
30	27.45	28.2	28.85	28.2	9.5	29.1
31	23.	23.1	22.95	23.	6.5	23.9

$X = 1.7$
$Y = 12.9$

This wire was straightened by heating slightly.

VIII

PIANO WIRE.

Diameter .82 m.m.

	Magnetic Data.				Photographic Data.	
				Average.	Original.	Transformed.
1	23.05	23.8	23.5	23.5	12.5	35.2
2	22.85	24.1	24.1	23.7	11.	32.6
3	27.3	27.15	26.9	27.1	10.5	31.8
4	30.3	30.9	30.1	30.4	11.75	[illegible]
5	34.	34.3	33.6	34.	12.75	35.7
6	36.35	36.4	35.8	36.1	13.	36.1
7	35.9	34.85	34.3	35.	12.	34.4
8	31.95	30.95	30.3	31.1	10.	30.9
9	26.25	26.35	25.85	26.2	6.5	24.8
10	23.55	24.2	23.95	23.9	3.75	20.1
11	22.45	22.95	23.2	22.9	2.5	17.9
12	24.3	23.35	23.5	23.7	3.5	19.7
13	26.3	24.85	24.5	25.2	5.5	23.1
14	26.1	24.35	24.1	24.9	5.5	23.1
15	23.95	21.9	21.9	22.6	3.25	19.2
16	21.4	19.3	19.4	20.	2.25	17.5
17	17.1	15.45	16.35	16.3	.75	14.9
18	14.45	13.45	14.2	14.	.25	14.
19	13.2	14.75	14.75	14.2	.25	14.
20	16.1	17.5	17.5	17.	1.5	16.2
21	19.55	21.45	21.2	20.7	4.	20.5
22	23.3	24.8	23.8	24.	6.75	25.3
23	24.75	26.1	25.35	25.4	9.25	29.6
24	25.25	26.8	25.9	26.	10.25	31.3
25	25.	26.2	25.4	25.5	9.75	30.5
26	23.25	24.8	24.1	24.1	8.	27.4
27	23.2	24.6	23.7	23.8	7.75	27.
28	23.7	25.2	24.5	24.4	9.	29.2
29	25.4	27.	26.6	26.3	10.5	31.8

X = 1.75
Y = 13.6

This wire was straightened by hammering.

IX

STEEL WIRE.

Diameter 1.09 m.m.

	Magnetic Data.				Photographic Data.	
				Average.	Original.	Transformed.
1	22.	22.15	22.2	22.1	1.	17.2
2	23.4	23.35	23.75	23.5	4.75	23.
3	23.75	24.1	24.25	24.	7.75	27.7
4	23.9	24.15	24.2	24.1	9.75	30.8
5	23.2	23.65	23.	23.2	9.	29.6
6	22.6	23.5	22.85	23.	7.	26.5
7	23.55	24.1	23.1	23.5	8.	28.1
8	25.5	26.05	25.6	25.7	9.5	30.4
9	28.7	28.75	28.8	28.7	10.5	32.
10	33.	32.9	32.8	32.9	11.5	33.5
11	33.6	33.55	33.55	33.6	11.5	33.5
12	30.2	30.25	30.4	30.3	10.	31.2
13	27.4	27.4	27.4	27.4	6.5	25.7
14	25.4	25.45	25.45	25.4	4.	21.2
15	25.1	25.15	25.	25.1	2.	18.7
16	27.5	27.45	27.3	27.4	2.5	19.5
17	28.5	28.35	28.25	28.4	4.5	22.6
18	27.7	27.7	27.7	27.7	4.5	22.6
19	25.15	25.2	25.25	25.2	3.5	21.1
20	21.35	21.4	21.4	21.4	2.25	19.1
21	18.15	18.15	17.9	18.1	1.25	17.6
22	16.1	16.2	16..	16.1	.25	16.
23	15.65	16.2	16.15	16.	.25	16.
24	18.7	19.1	19.	18.9	2.	18.7
25	21.6	21.7	21.4	21.6	4.75	23.
26	24.4	24.3	23.75	24.2	7.25	26.9
27	26.3	26.25	25.85	26.1	9.	29.6
28	26.55	26.45	26.2	26.4	10.25	31.6

$X = 1.56$
$Y = 15.61$

This wire was hammered straight.

The current was only half that used for the smaller wires.

STEEL WIRE.

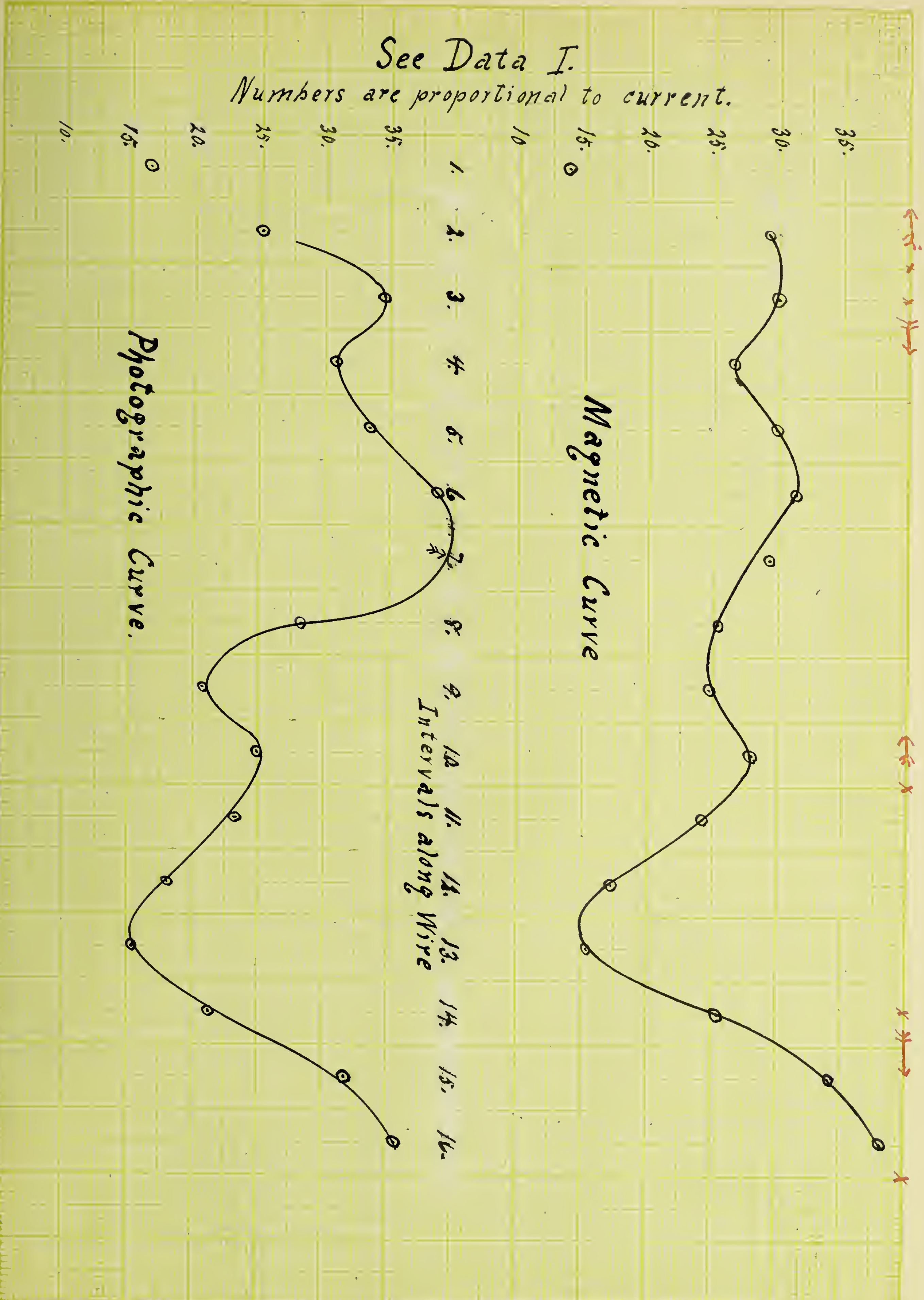
Diameter 1.99 m.m.

	Magnetic Data.				Photographic Data.	
				Average.	Original.	Transformed.
1	27.25	26.9	26.9	27.	5.	21.8
2	27.15	26.75	26.6	26.8	6.75	24.5
3	27.6	27.05	26.85	27.1	8.	26.4
4	28.15	27.75	27.15	27.7	9.25	28.3
5	29.3	28.9	28.75	29.	10.5	30.3
6	30.25	29.7	29.75	29.9	11.25	31.4
7	29.65	29.05	28.95	29.2	10.25	30.
8	28.35	27.9	27.55	27.9	7.	24.9
9	25.7	25.35	25.4	25.2	4.	20.2
10	23.45	23.2	23.15	23.3	2.	17.1
11	23.9	23.6	23.7	23.7	1.75	16.6
12	25.5	25.05	25.	25.1	4.	20.2
13	25.5	25.3	25.25	25.4	3.75	19.8
14	23.65	23.5	23.6	23.4	2.75	18.3
15	19.6	19.2	19.4	19.4	1.25	15.9
16	16.75	16.7	16.45	16.6	.25	14.4
17	14.05	14.35	14.25	14.2	0.0	14.
18	13.7	14.2	14.2	14.	.25	14.4
19	16.95	17.2	17.25	17.1	2.5	17.9
20	20.05	20.1	20.05	20.	5.75	22.9
21	22.6	22.3	22.1	22.3	8.	26.4
22	23.75	23.4	23.25	23.5	9.75	29.1
23	23.25	23.1	22.9	23.1	8.75	27.6
24	22.15	21.9	21.85	21.9	7.25	25.2
25	22.	21.55	21.4	21.7	7.75	26.
26	23.3	22.75	22.55	22.8	8.75	27.6
27	25.7	25.1	24.95	25.3	9.75	29.1
28	29.3	28.75	28.4	28.8	10.5	30.3
29	32.15	31.75	31.65	31.9	11.5	31.8
30	32.8	32.5	32.55	32.6	12.	32.6

$X = 1.55$
$Y = 14.$

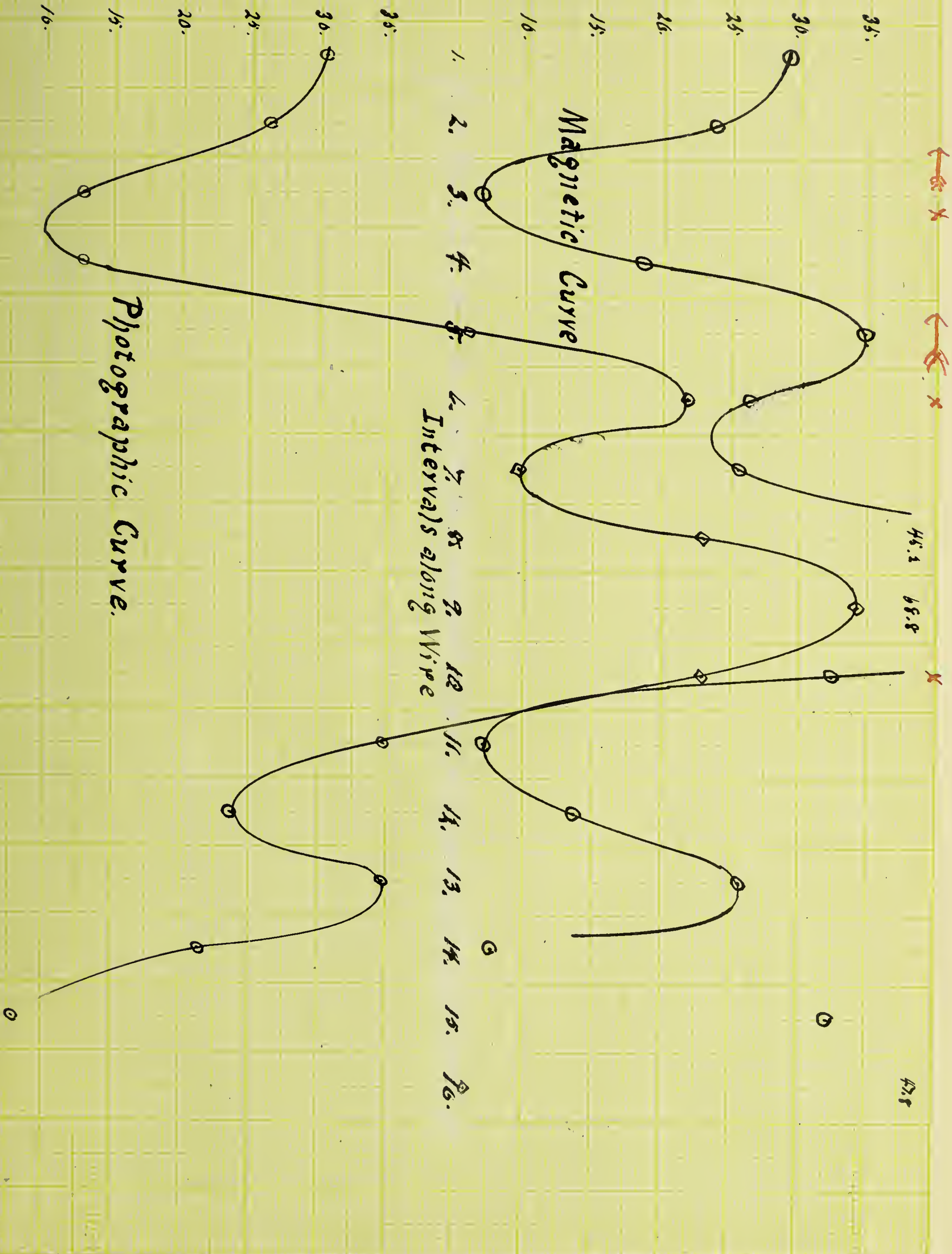
This wire was straightened by heating.

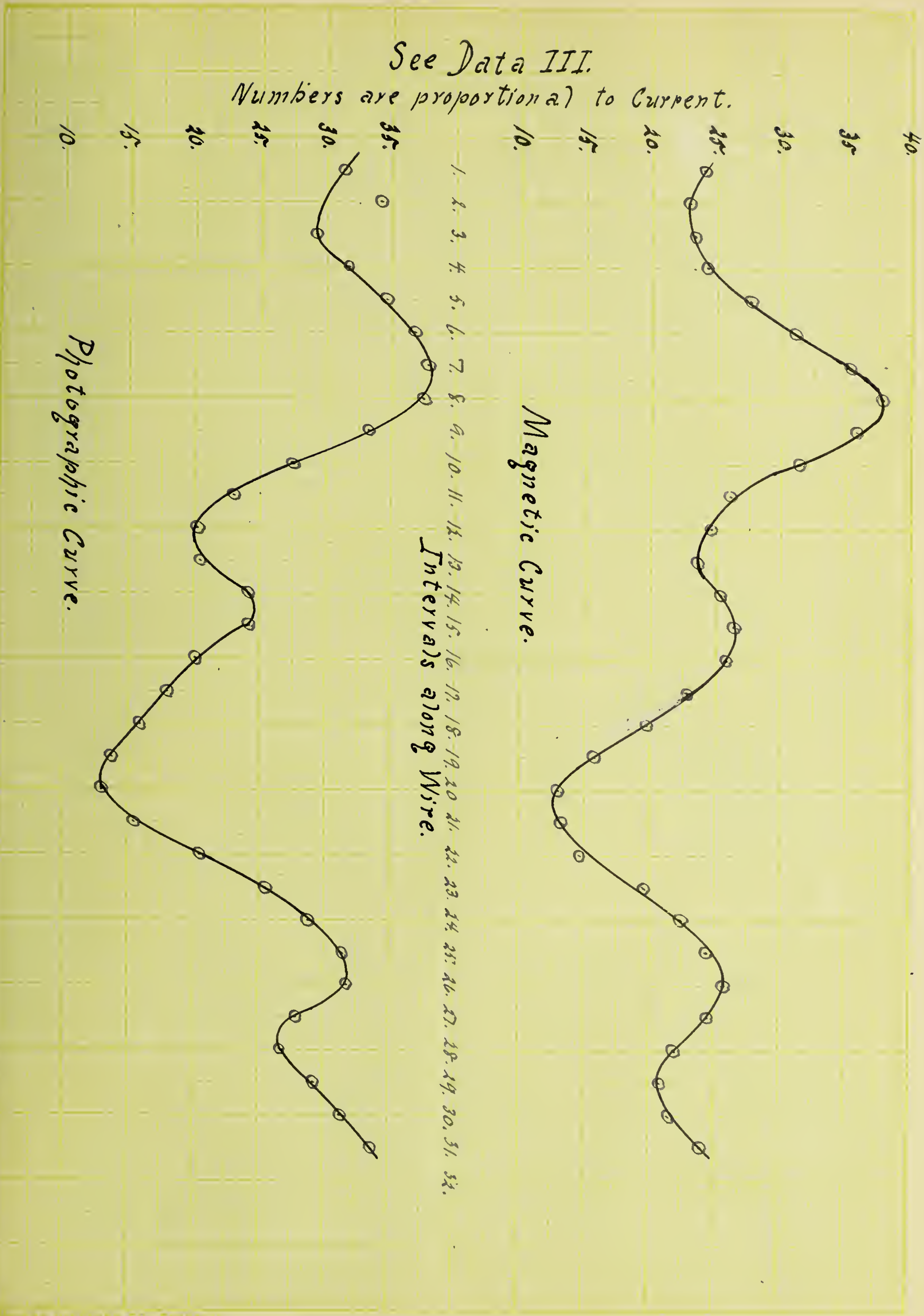
The current was only half that used in the case of the smaller wire.


See Data I.
Numbers are proportional to current.
Magnetic Curve
Photographic Curve.
Intervals along Wire
1. 2. 3. 4. 5. 6. 7. 8. 9. 10. 11. 12. 13. 14. 15. 16.
10. 15. 20. 25. 30. 35.
10 15. 20. 25. 30. 35.

See Data II

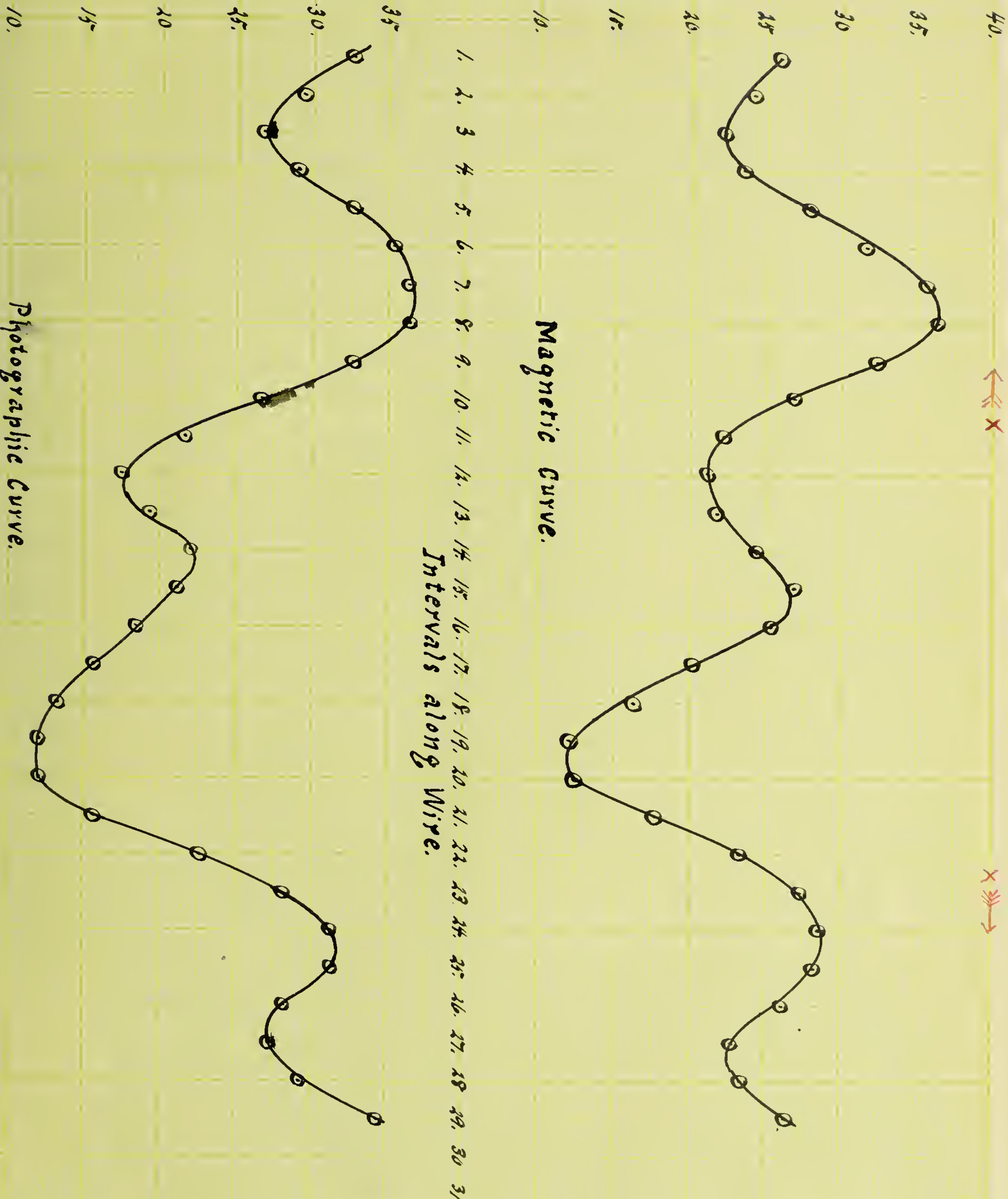
Numbers are proportional to Current.

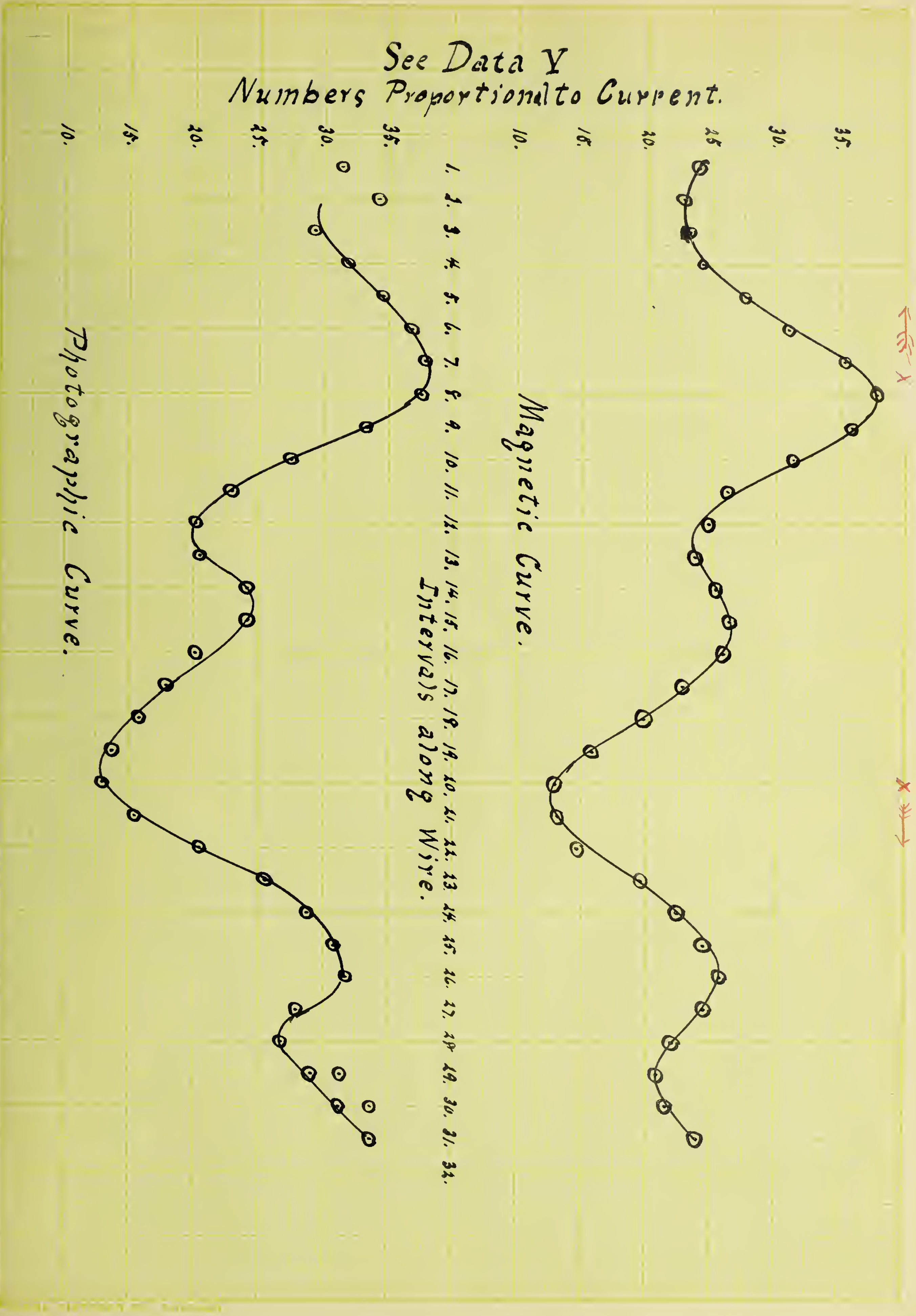



See Data III.
Numbers are proportional to Current.
Magnetic Curve.
Photographic Curve.
Intervals along Wire.
1. 2. 3. 4. 5. 6. 7. 8. 9. 10. 11. 12. 13. 14. 15. 16. 17. 18. 19. 20. 21. 22. 23. 24. 25. 26. 27. 28. 29. 30. 31. 32.
10. 15. 20. 25. 30. 35. 40.
10. 15. 20. 25. 30. 35.

See Data IV.

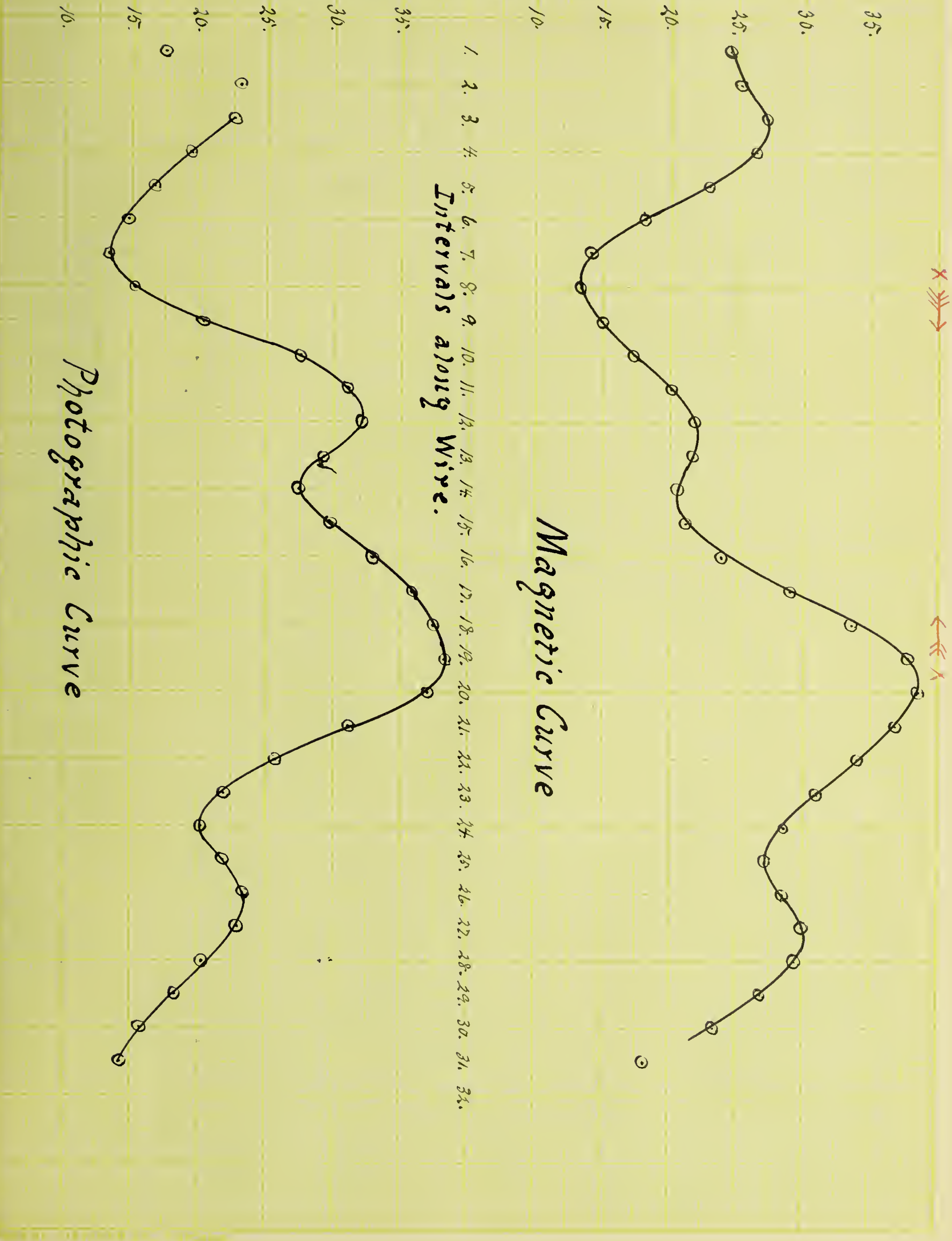
Numders proportion to Current.



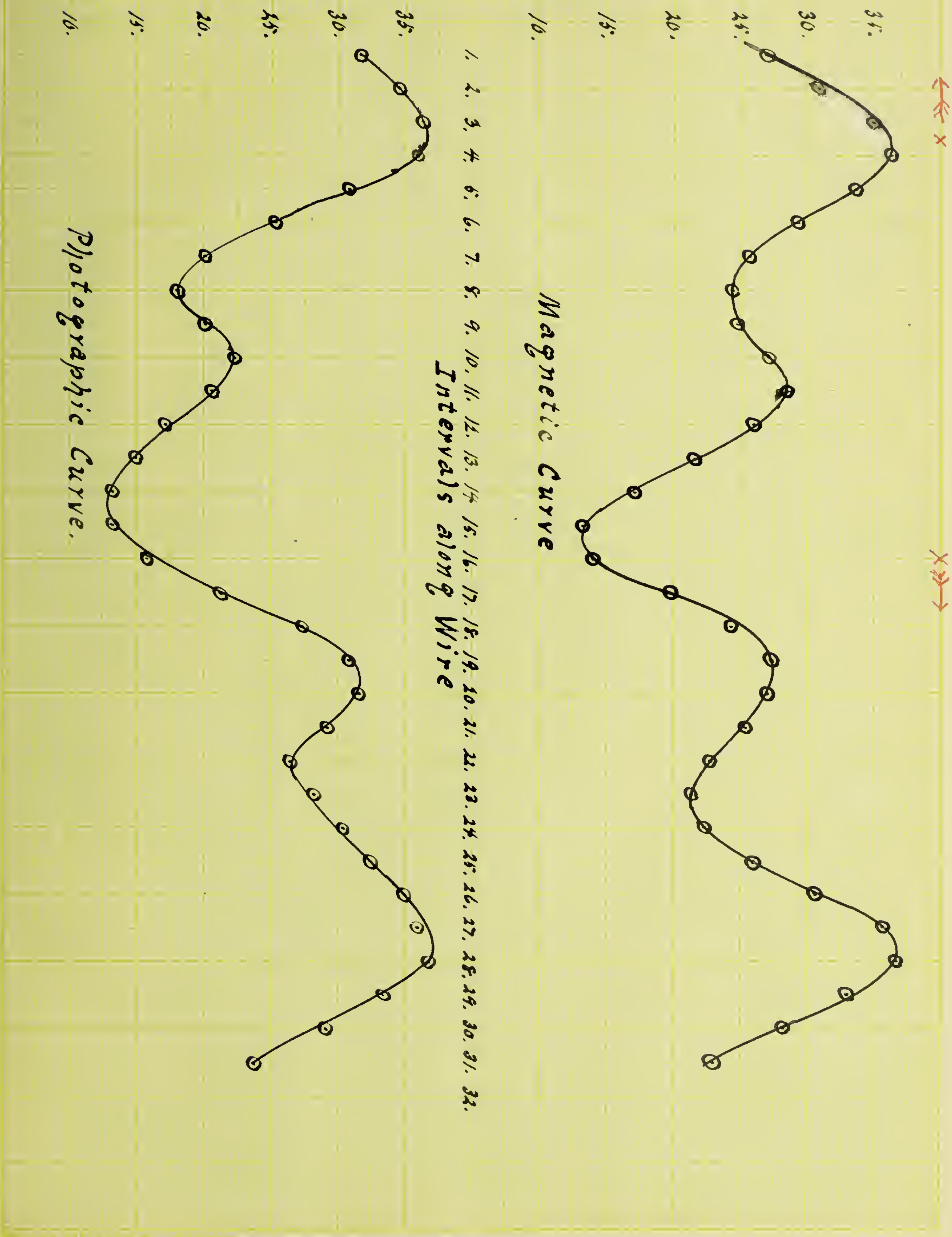

See Data Y
Numbers Proportional to Current.
Magnetic Curve.
Photographic Curve.
Intervals along Wire.
10.
15.
20.
25.
30.
35.
1. 2. 3. 4. 5. 6. 7. 8. 9. 10. 11. 12. 13. 14. 15. 16. 17. 18. 19. 20. 21. 22. 23. 24. 25. 26. 27. 28. 29. 30. 31. 32.

See Data VI

Numbers Proportional to Current

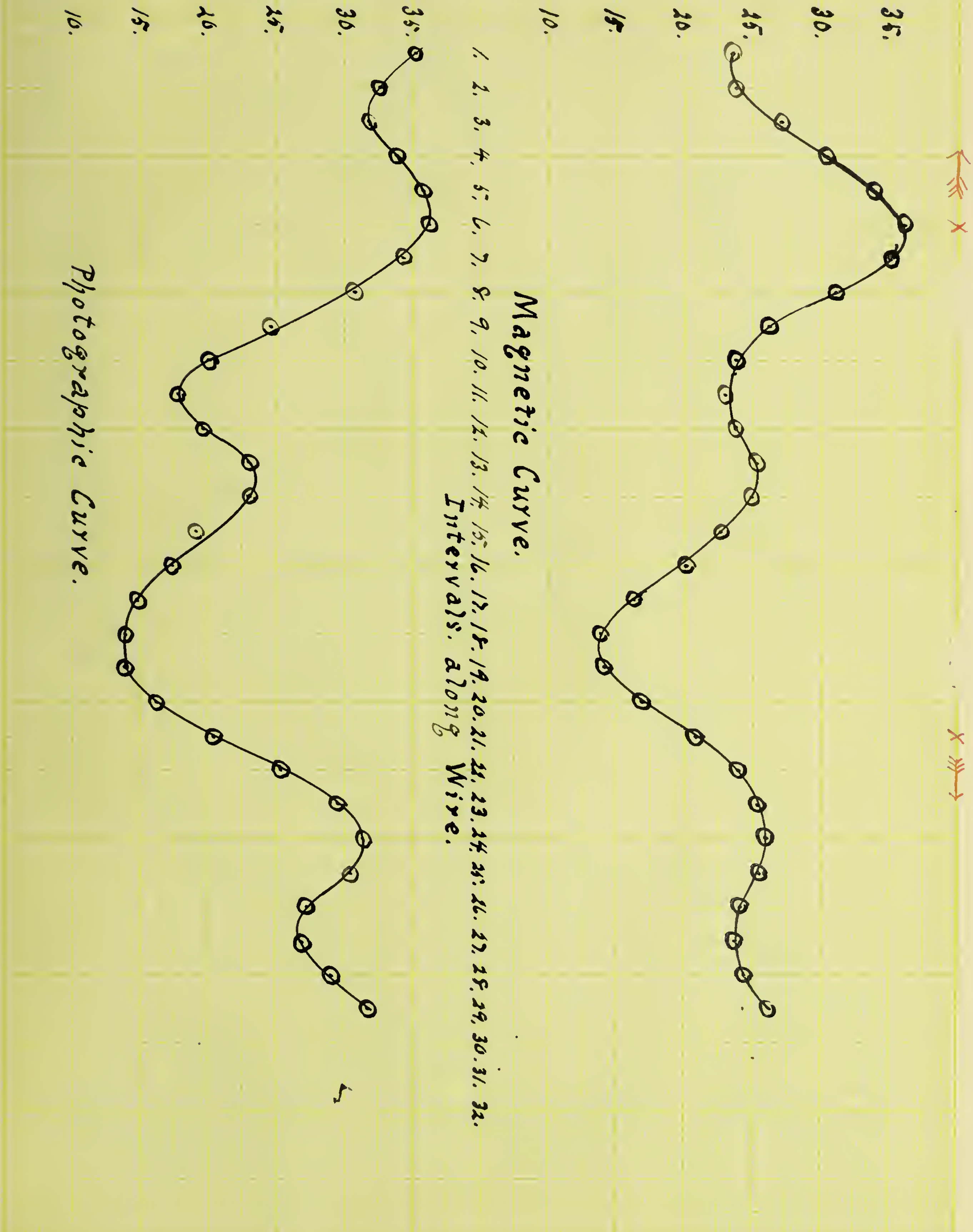


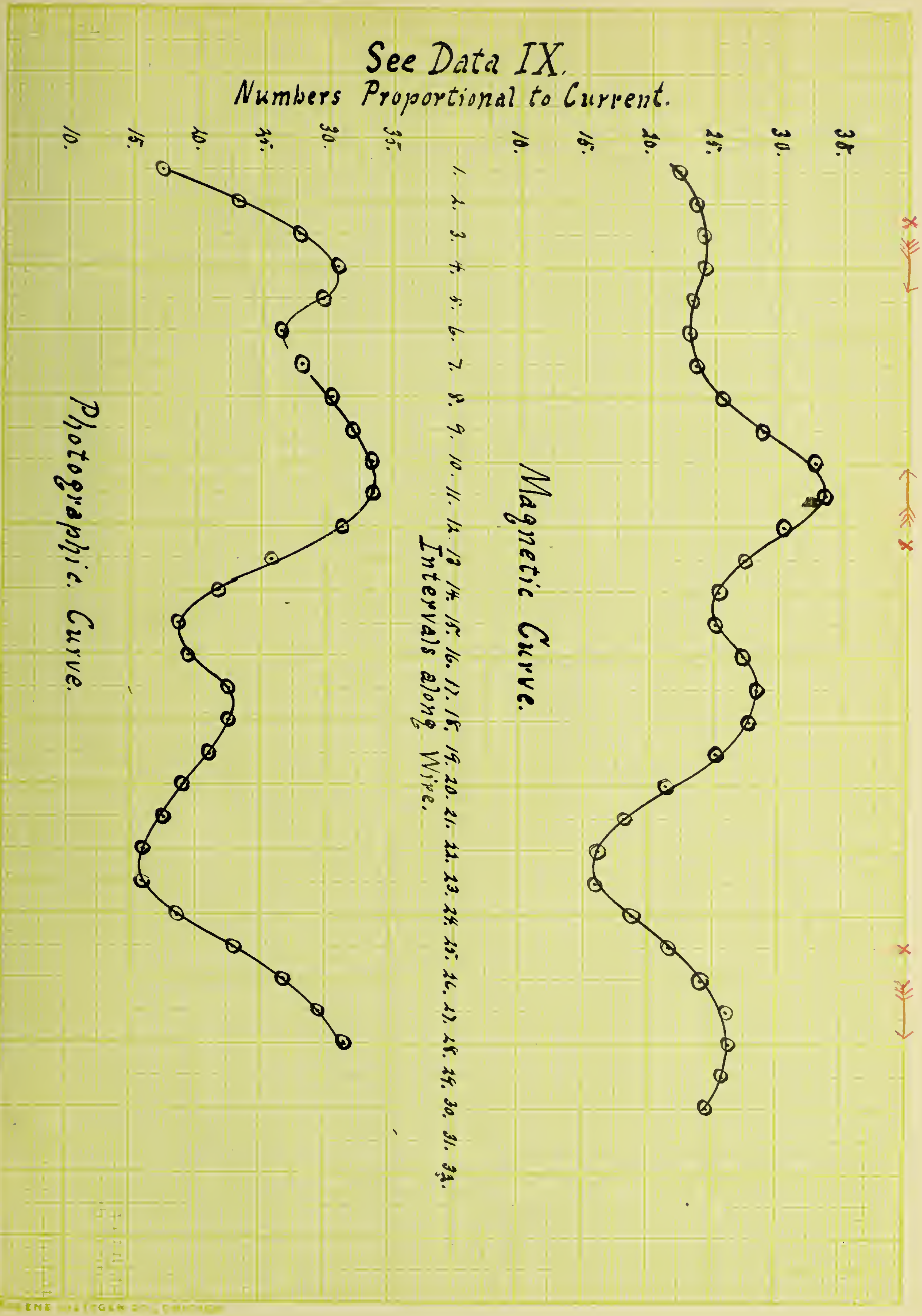
See Data VII
Numbers Proportional to Current.



See Data VIII

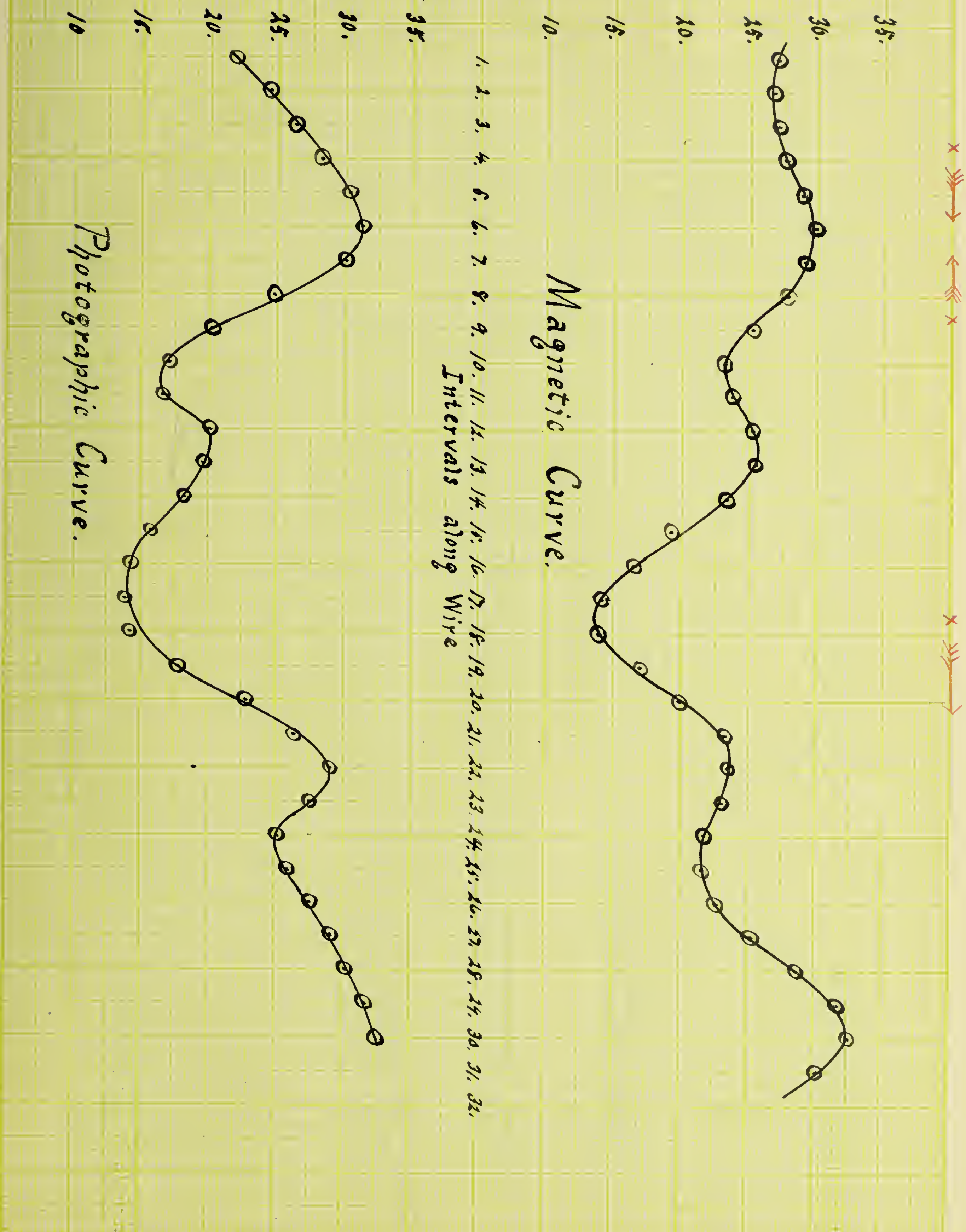
Numbers Proportional to Current.



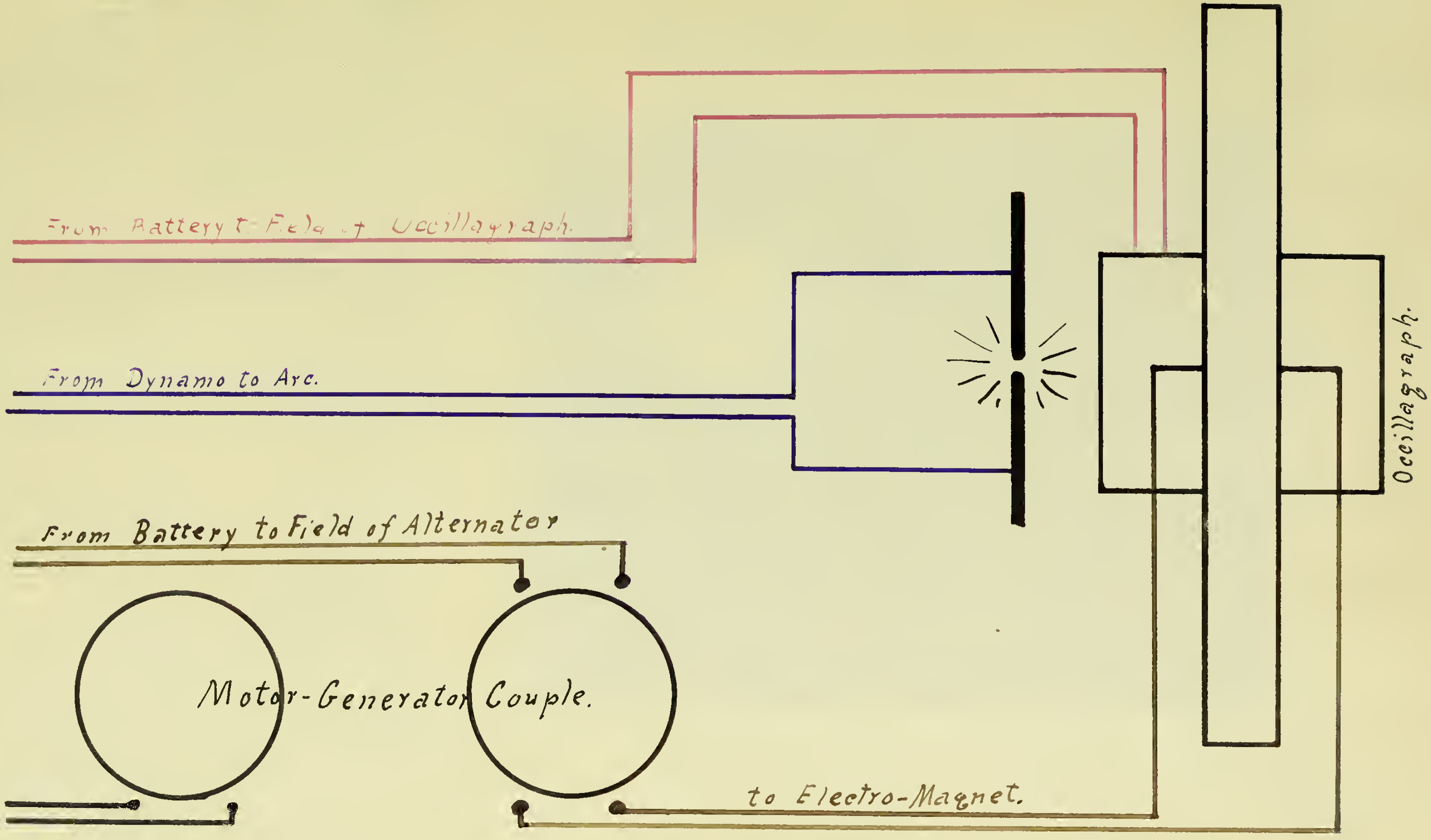

See Data IX.
Numbers Proportional to Current.
10. 15. 20. 25. 30. 35.
Magnetic Curve.
1. 2. 3. 4. 5. 6. 7. 8. 9. 10. 11. 12. 13. 14. 15. 16. 17. 18. 19. 20. 21. 22. 23. 24. 25. 26. 27. 28. 29. 30. 31. 32.
Intervals along Wire.
10. 15. 20. 25. 30. 35.
Photographic Curve.

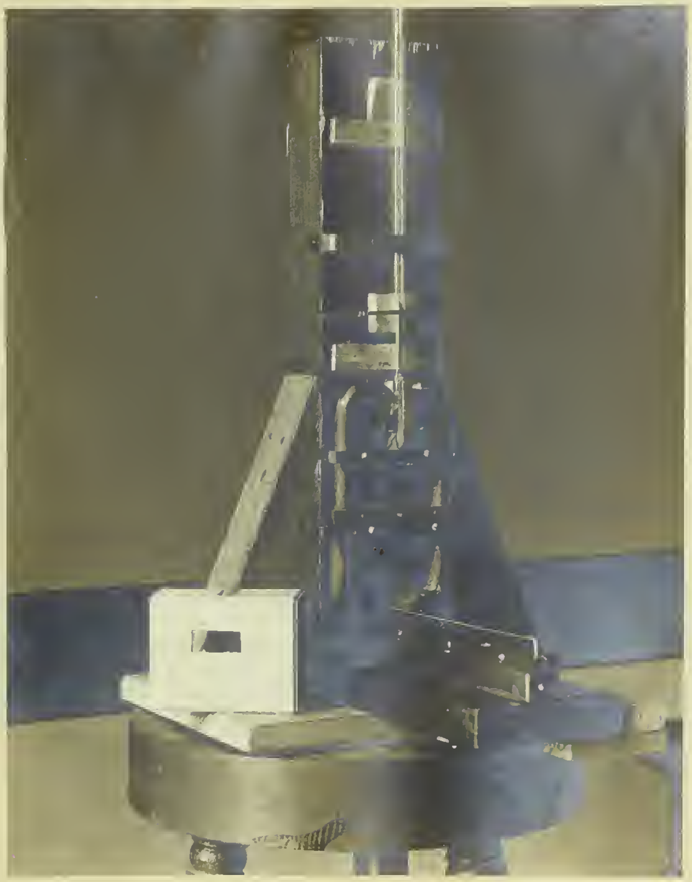
See Data X.

Numbers Proportional to Current.

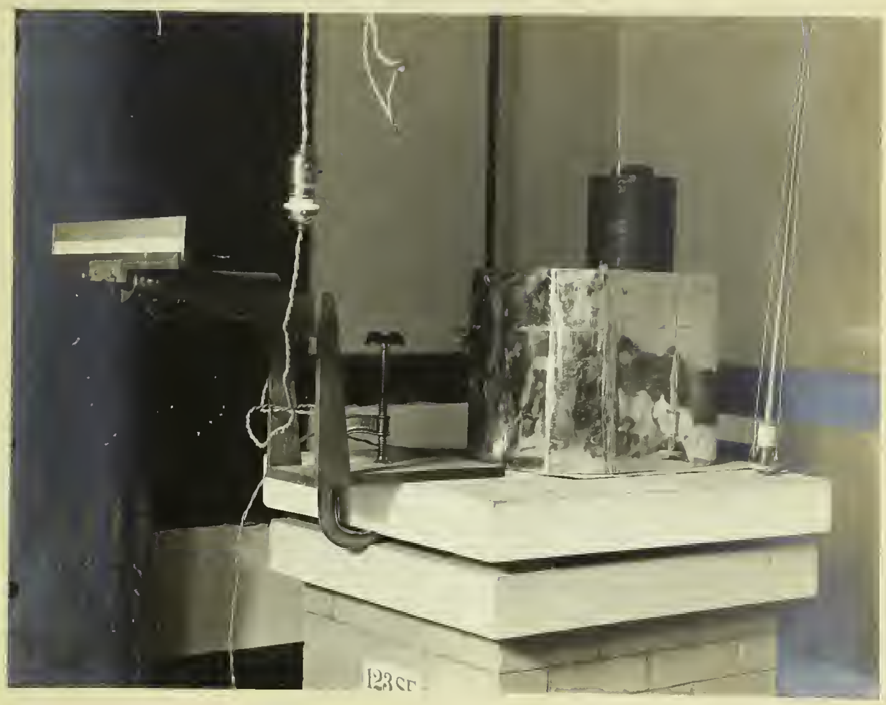


Connections of Apparatus.

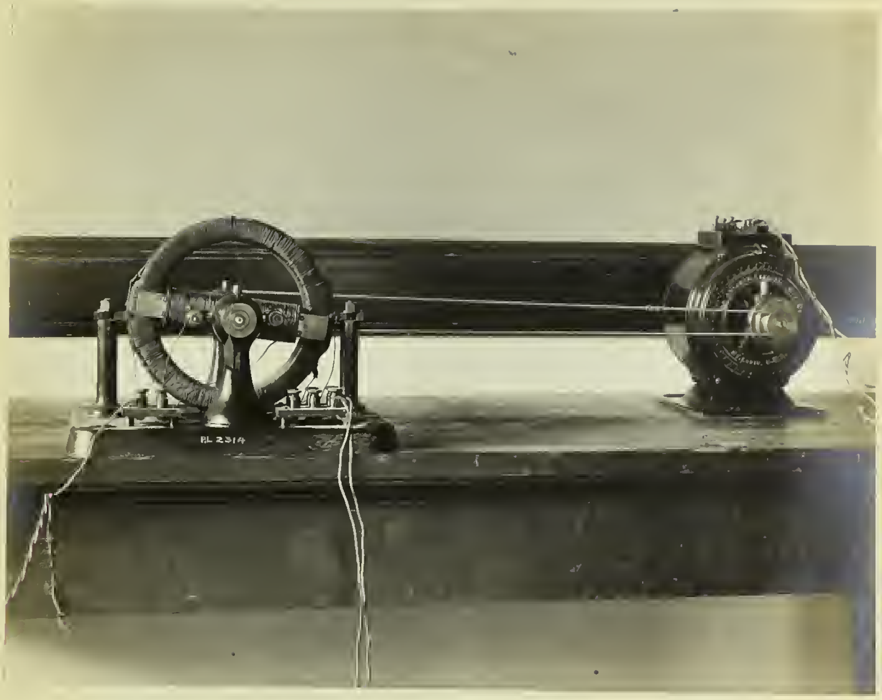




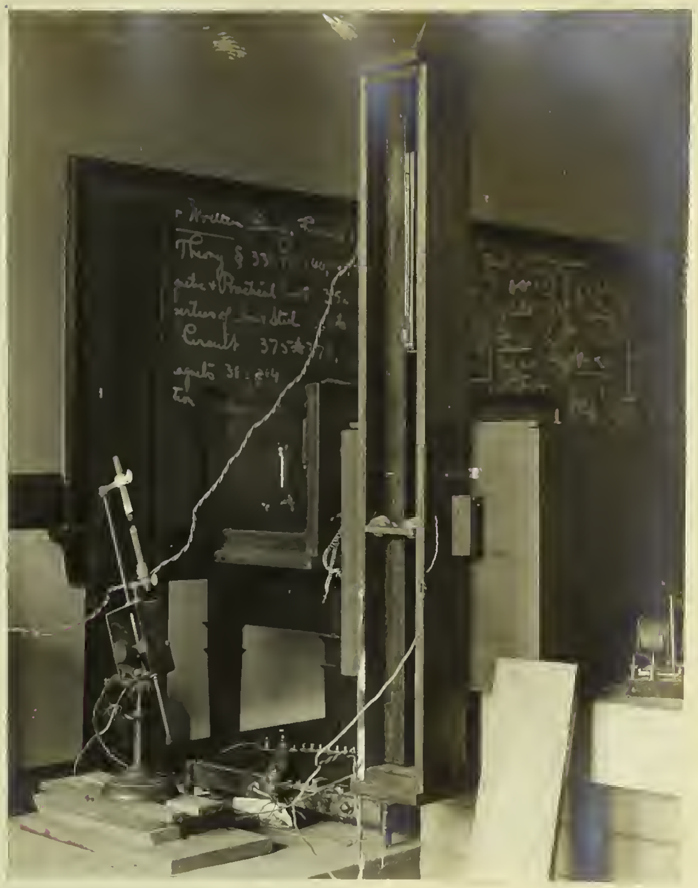
Magnetometer system with gas pipe and tin missing. The card-board box at the bottom left hand corner belongs about the magnetometer in the middle of the figure. The carriage is also in position for testing.



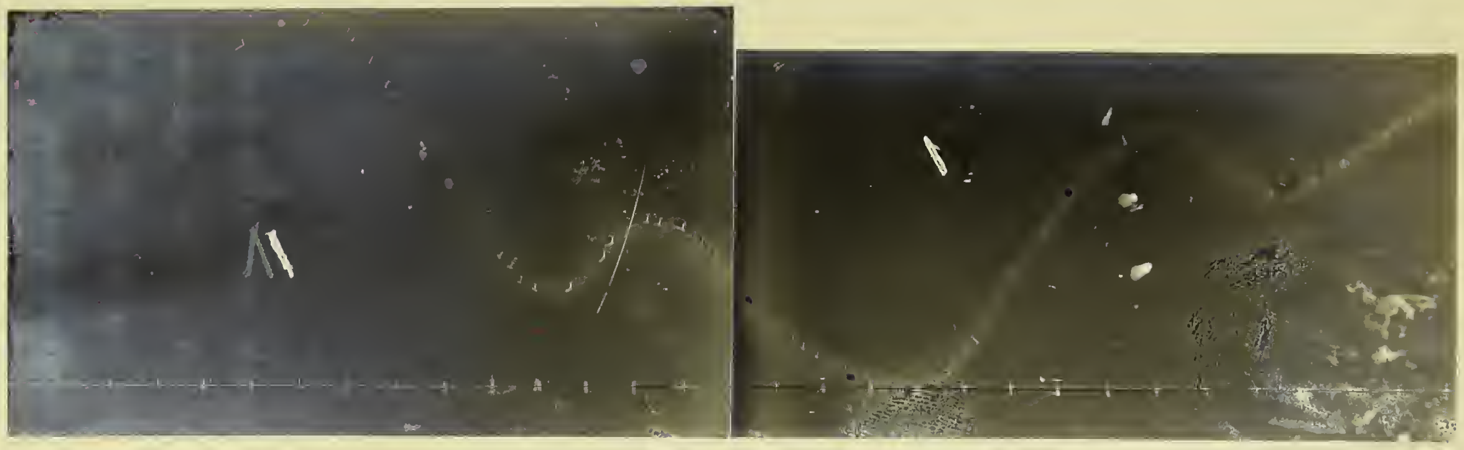
This picture shows the testing apparatus complete. At the extreme right is the first magnetic testing apparatus discribed early in this paper.



This picture shows how we obtained the low frequency alternating current. The one to the left is the generator and is one designed to give an alternating current which can be represented by a sin curve.



This picture shows the photographic box in its proper position on the occillagraph. The back of the box is removed to show the inside of the box and to show the position of the magnet and also the carriage before exposure.



Sample of Optic Curve.